# CLOUD FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

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October 20, 2014

*www.ecd.bnl.gov/steve*

# CLOUD FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

# SHORT ABSTRACT

No.

No.

No.

*I come to bury cloud fraction, not to praise it.*

*- Shakespeare, 1599*

# CAN CLOUD FRACTION BE DEFINED?

# WHAT IS A CLOUD?

*AMS Glossary of Meteorology (2000)*
A *visible aggregate* of minute water droplets and/or ice particles in the atmosphere above the earth's surface.
**Total cloud cover**: Fraction of the sky hidden by all *visible clouds*.

*Ramanathan, JGR (ERBE, 1988)*
Cloud cover is a *loosely defined term*.

*Clothiaux, Barker, & Korolev (2005)*
Surprisingly, and in spite of the fact that we deal with clouds on a daily basis, to date there is *no universal definition of a cloud*. . . . Ultimately, the definition of a cloud *depends on the threshold sensitivity* of the instruments used.

*Potter Stewart (U.S. Supreme Court, 1964)*
I shall not today attempt further to define it, but *I know it when I see it*.

# WHY DO WE WANT TO KNOW CLOUD FRACTION?

Clouds have a strong impact on Earth's radiation budget: -45 W m$^{-2}$ shortwave; +30 W m$^{-2}$ longwave.
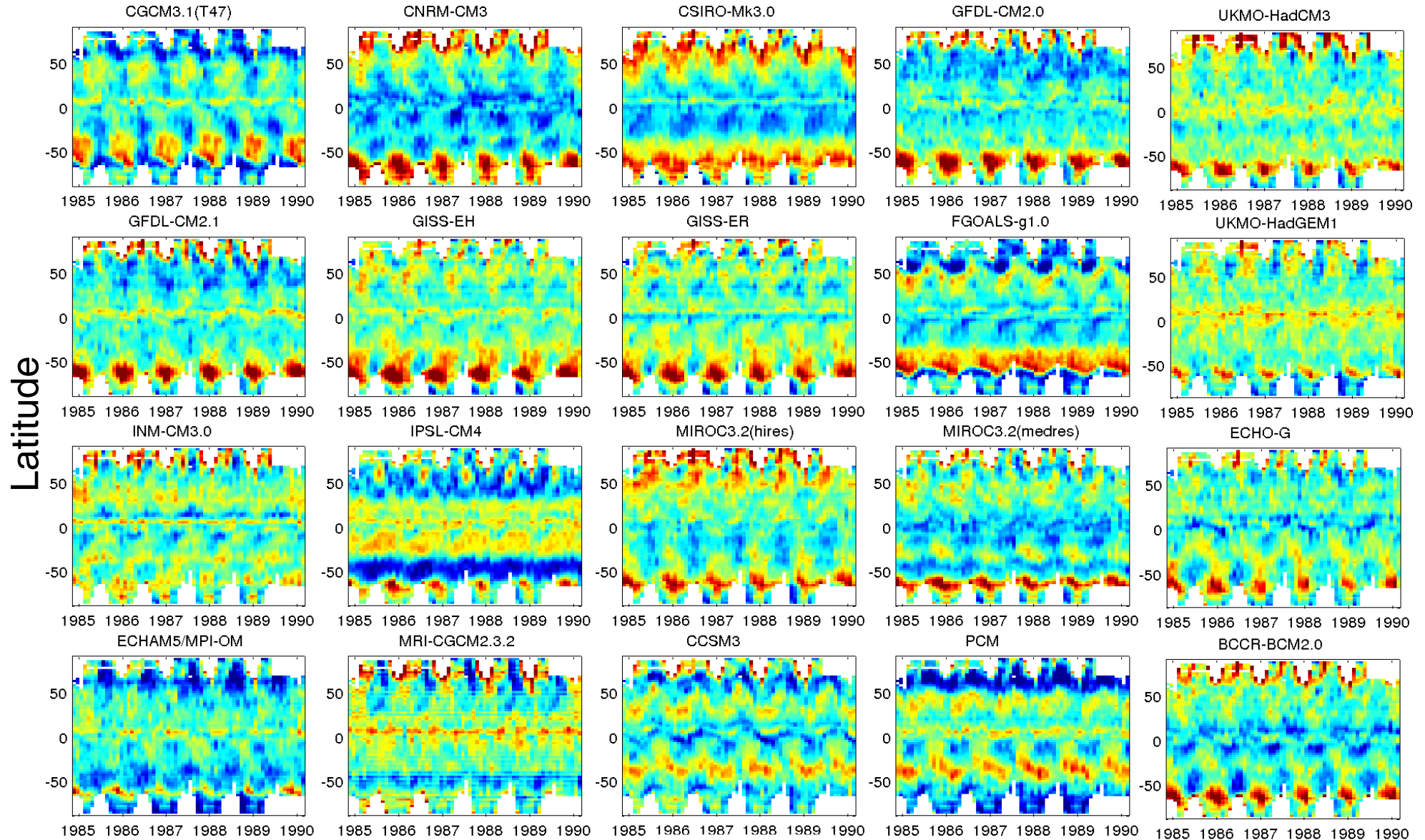
Slight change in cloud fraction could augment or offset greenhouse gas induced warming – cloud feedbacks.

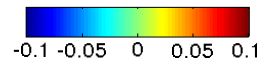Accurate representation of cloud radiative effects is essential in climate models.

Getting cloud fraction "right" is an evaluation criterion for global climate models.

# ZONAL MONTHLY MEAN ALBEDO
## 20 GCMs – Difference vs. ERBE Satellite



Obs < Model – Model is bright

Obs > Model – Model is dark

*Modified from Bender et al., Tellus, 2006*

# WHY DO WE WANT TO KNOW CLOUD FRACTION?

*One commonly encounters analyses such as*

Here the outgoing long-wave flux for a unit area with fraction $A_c$ covered by clouds (i.e., $A_c$ is the overcast fraction of the sky) will be considered and the following symbols are defined.

$F_c$    flux from the clear-sky regions;
$F_0$    flux from the overcast sky;
$F$    cloudy-sky (clear plus overcast) flux;
$A_c$    cloud-cover fraction.

With the above definitions, one can write

$$F = F_c(1 - A_c) + F_0 A_c$$

*This assumes that there are unique values for $F_c$, $F_0$, and $A_c$.*

# CAN CLOUD FRACTION
# BE MEASURED?

## Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land

### Oktas – eighths of the sky

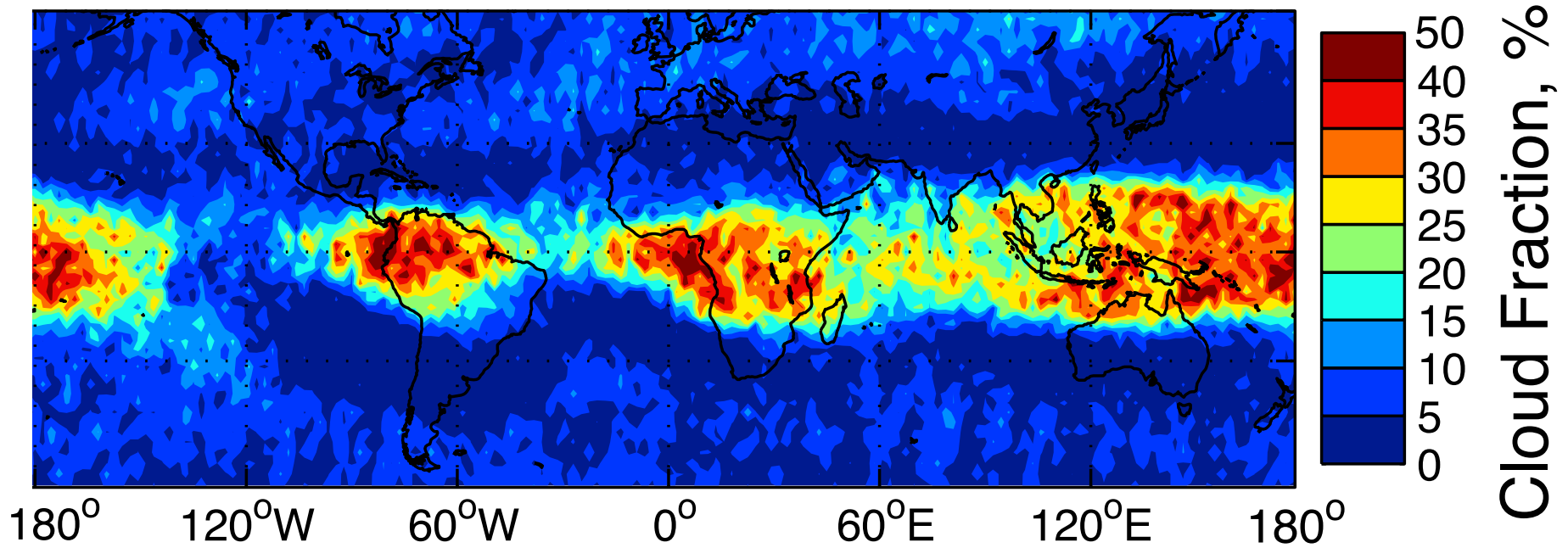| Domain | Observations Millions | Cloud cover % |
|---|---|---|
| Land | 116 | 52.4 |
| Ocean | 43.3 | 64.8 |
| Global | 159 | 61.2 |
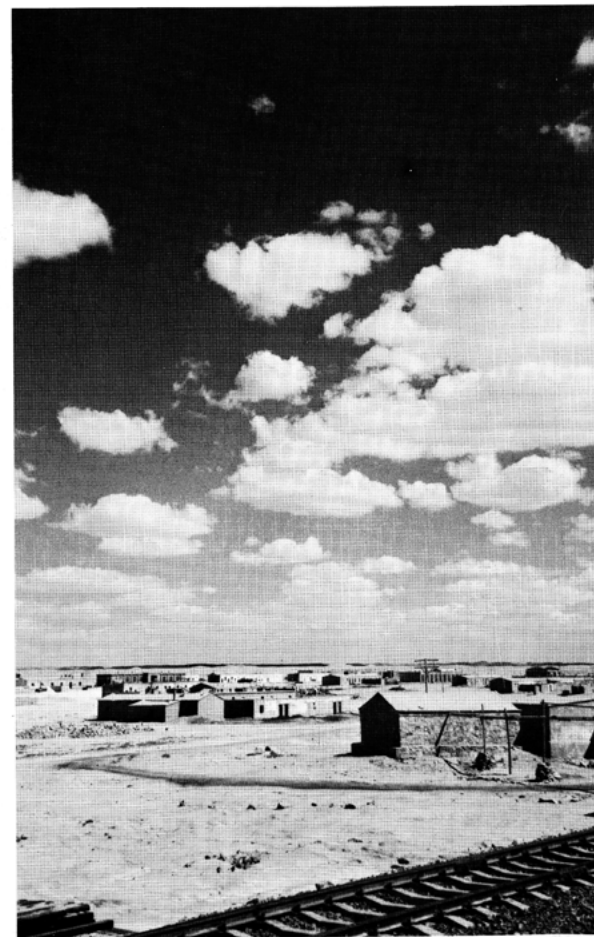
*Warren, Hahn, London, Chervin, Jenne*

# OPTICALLY THIN CLOUDS CAN BE PREVALENT IN TROPICS

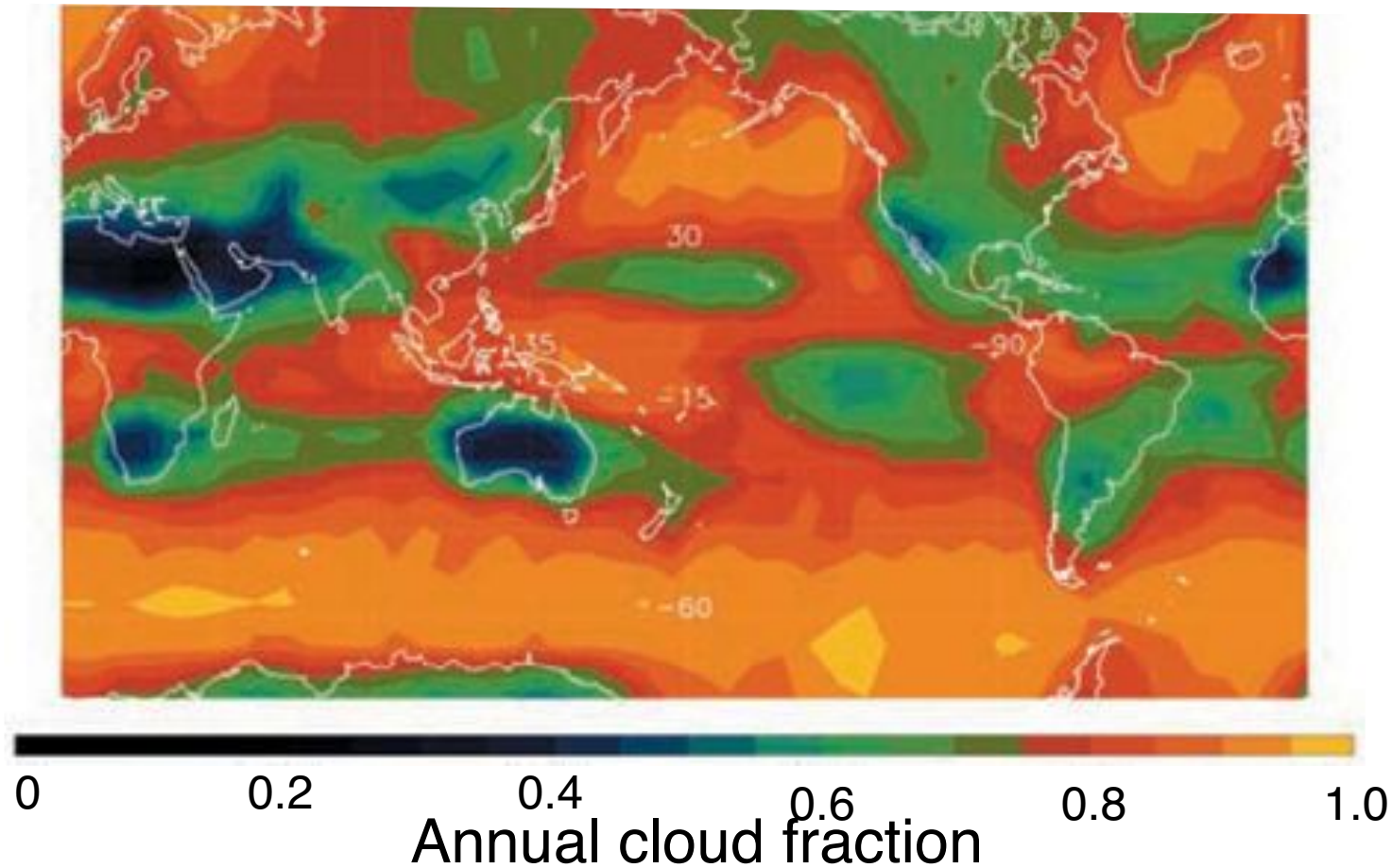## Subvisible cirrus detected by lidar from space, DJF

$$0.01 \leq \tau \leq 0.03$$



*Martins Noel & Chepfer, JGR, 2011*

# GEOGRAPHICAL DISTRIBUTION OF CLOUD FRACTION

## Cloudsat Calipso Product



*Mace, ... Stephens, Trepte, Winker, JGR 2009*

Annual cloud fraction varies widely as function of location.

# SATELLITE ESTIMATES OF CLOUD FRACTION
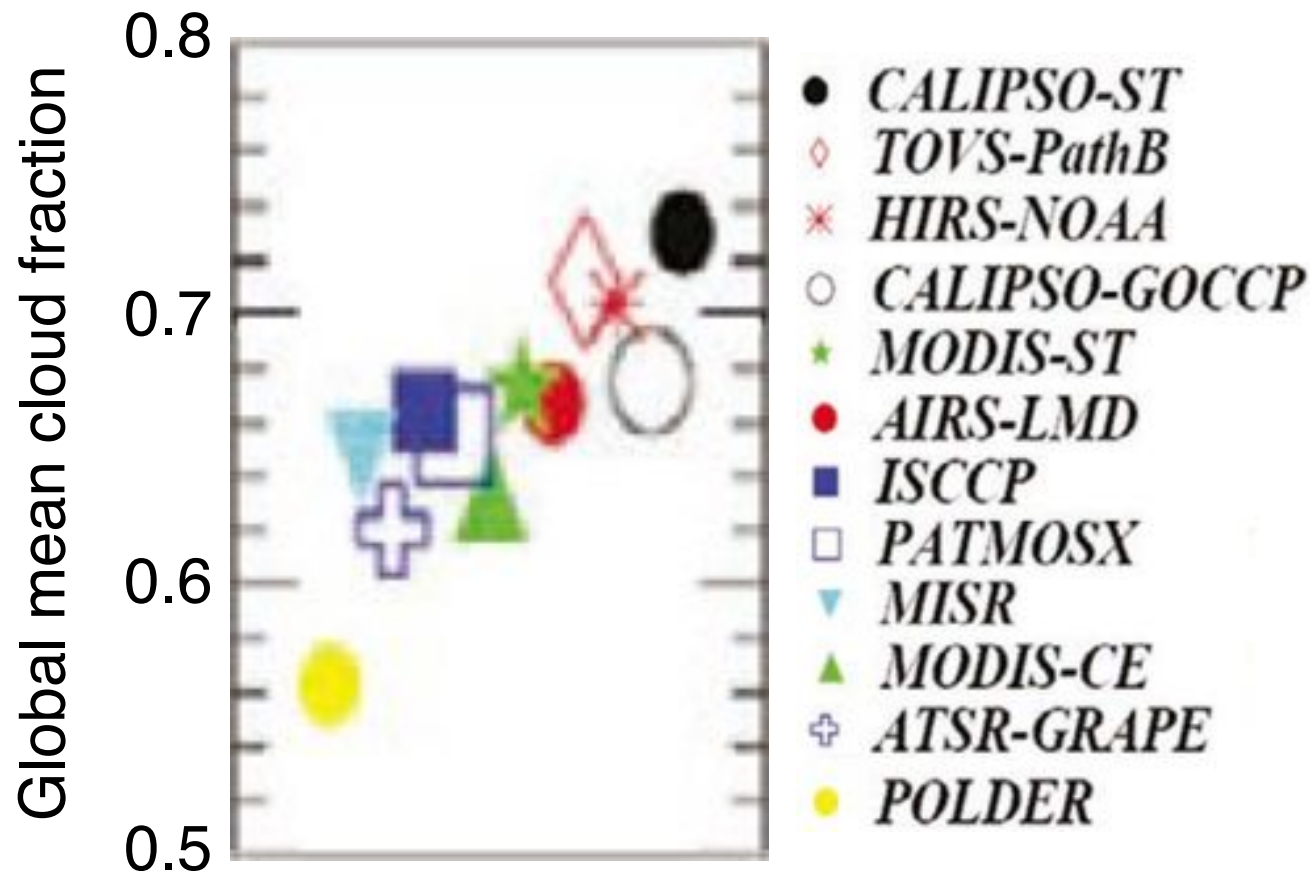


- Global total cloud amount (fractional cloud cover) is about 0.68 (±0.03), when considering clouds with optical depth > 0.1.

- The value increases to 0.73 when including subvisible cirrus with optical depth down to 0.01 (e.g. CALIPSO) and decreases to about 0.56 for clouds with optical depth > 2 (e.g. POLDER).

*Stubenrauch, Rossow, ... Ackerman, ... Chepfer, DiGirolamo, ... Winker et al., BAMS, 2013*

# PERSISTENT <span style="color:red">VERY THIN</span> CIRRUS AT MIDLATITUDE SITE
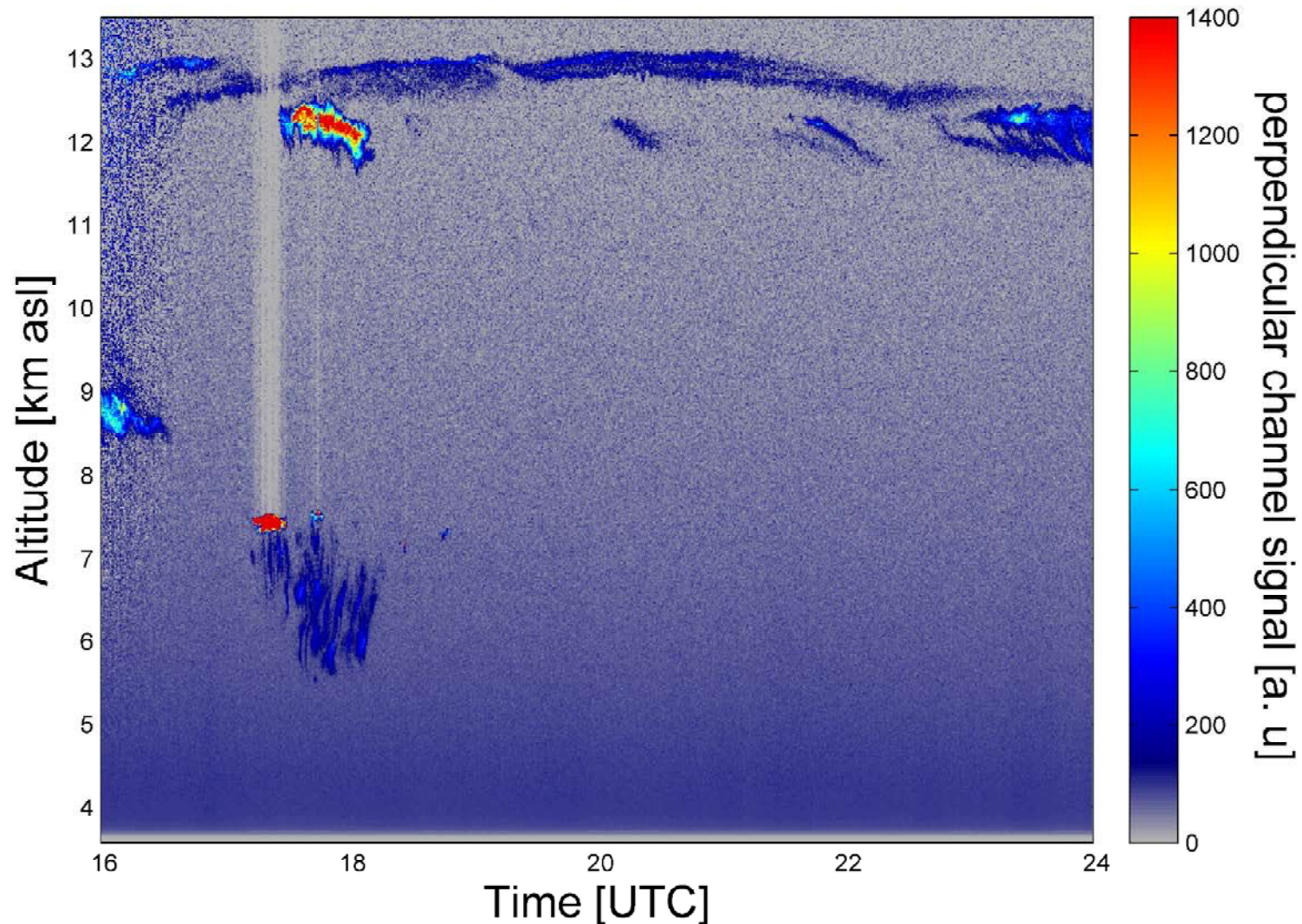


*Kienast-Sjögren et al., 9th Int. Symp. on Tropospheric Profiling, 2012*

Optical depth of cirrus layer estimated from lidar return as **0.003 to 0.004**.

# GLOBAL AND ANNUAL MEAN RADIATIVE FLUXES AND CLOUD RADIATIVE EFFECT FROM ERBE

## Seasonal Variation of Cloud Radiative Forcing Derived From the Earth Radiation Budget Experiment

E. F. Harrison, P. Minnis, B. R. Barkstrom, V. Ramanathan, R. D. Cess, and G. G. Gibson

The effects of clouds on Earth's radiation balance are examined as the difference between the **cloud-free** and the **all-sky** radiative fluxes. This difference is defined as **cloud-radiative forcing** (cloud radiative effect).
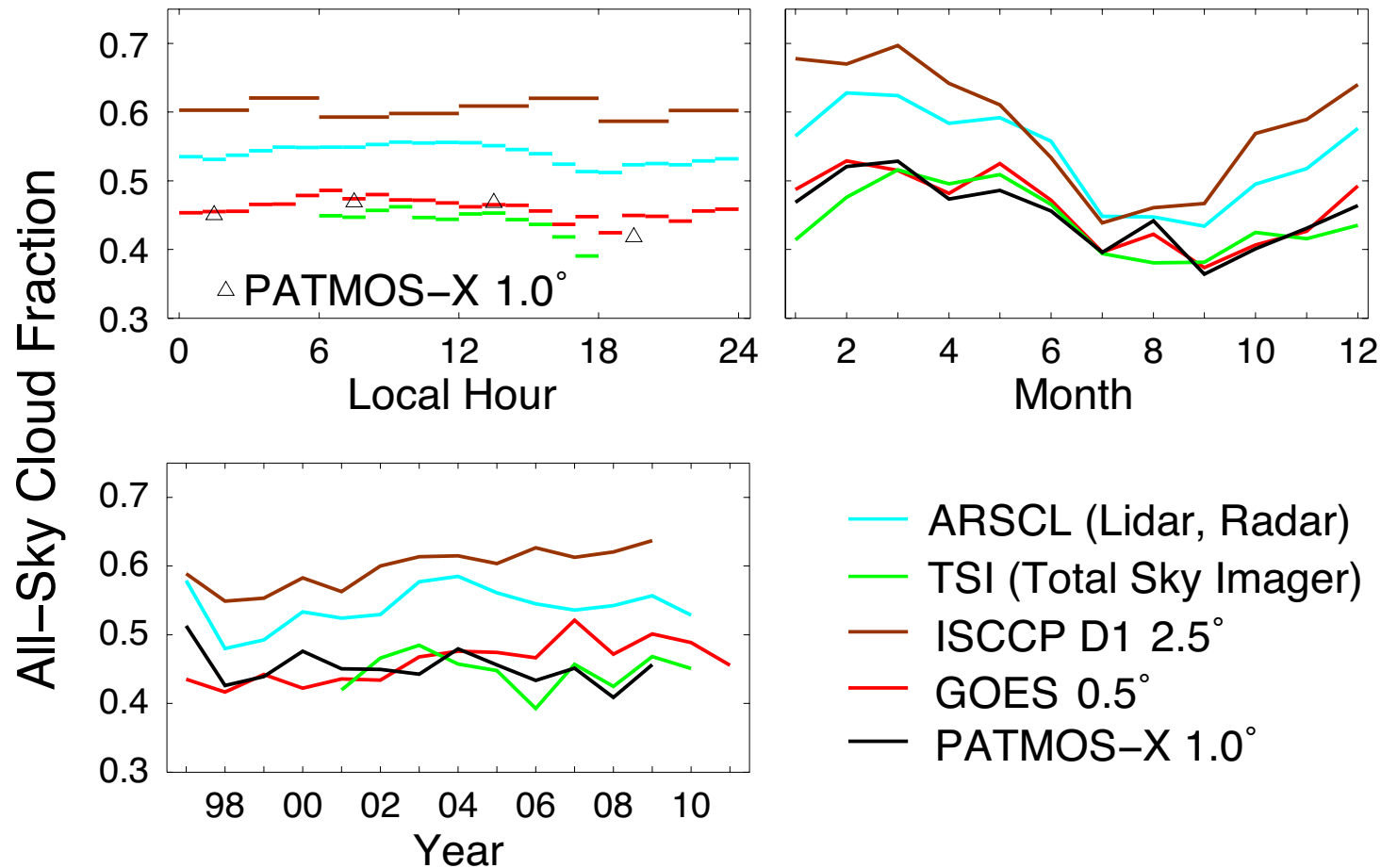
|  | All-Sky | Cloud-Free | CRE | $d$CRE/$d$CF* |
|---|---|---|---|---|
|  | W m$^{-2}$ | W m$^{-2}$ | W m$^{-2}$ | W m$^{-2}$ %$^{-1}$ |
| Shortwave absorbed | 239.3 | 287.7 | -48.4 | -0.7 |
| Longwave emitted | 234.5 | 265.6 | 31.1 | 0.4 |
| Net | 4.8 | 22.1 | -17.3 | -0.3 |

Uncertainties ~ 5 W m$^{-2}$.

*For global-average cloud cover 70%.

# CLOUD FRACTION BY MULTIPLE METHODS

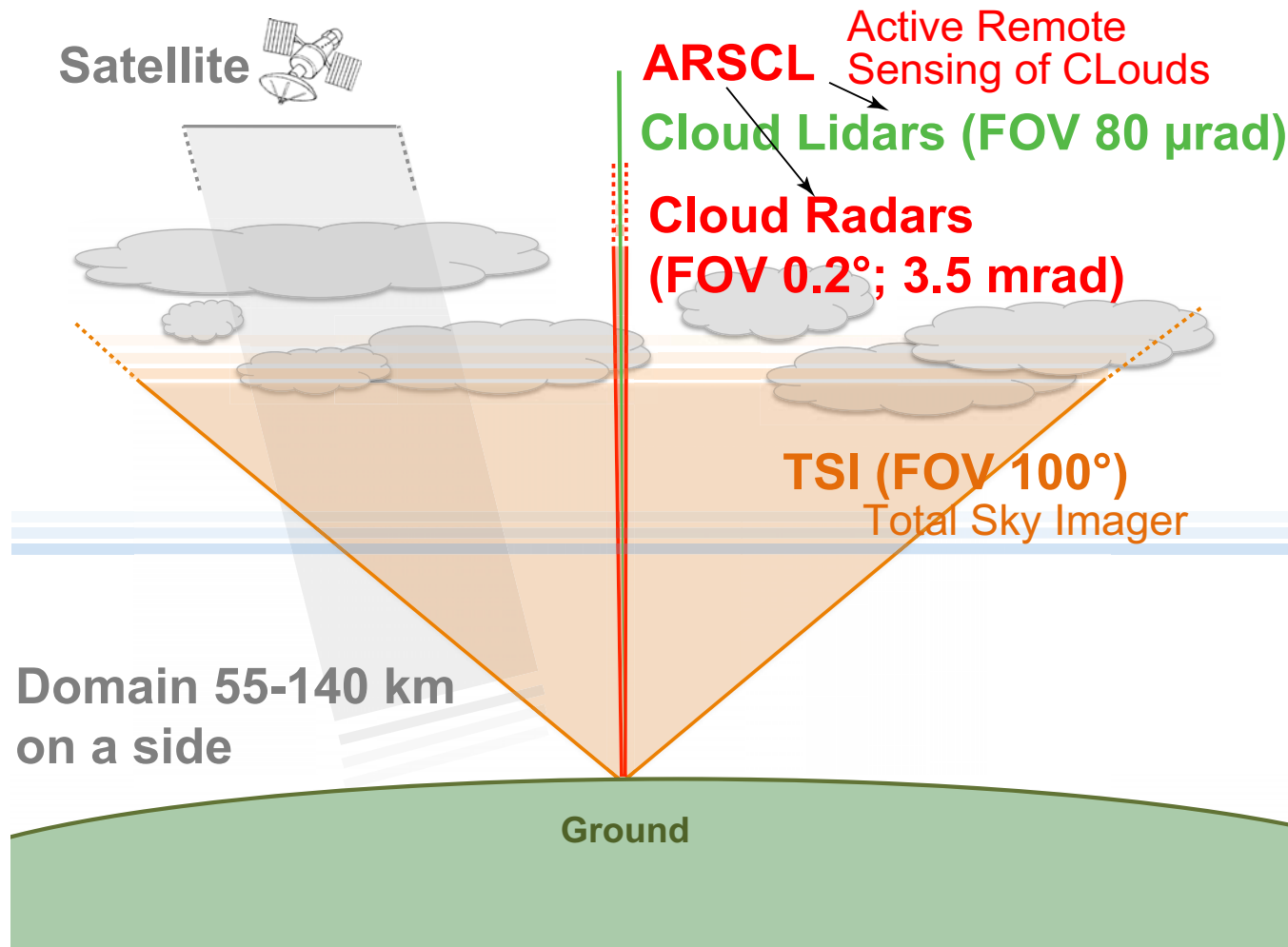2 Surface, 3 satellite methods at U.S. Southern Great Plains; 10 years data



*Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014*

Different methods yield ***substantial systematic differences in the mean***.

Error of 0.1 in cloud fraction is ~ 7 W m$^{-2}$ in shortwave, 4 W m$^{-2}$ in longwave.

# MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION



**Satellite**

**ARSCL** — Active Remote Sensing of CLouds

**Cloud Lidars (FOV 80 μrad)**

**Cloud Radars (FOV 0.2°; 3.5 mrad)**

**TSI (FOV 100°)** Total Sky Imager

**Domain 55-140 km on a side**

**Ground**

*Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014*

Although different approaches yield different instantaneous, local CF, they would be expected to yield the same *average* CF.

# CORRELATION OF CLOUD FRACTION BY DIFFERENT METHODS

Hourly cloud fraction at SGP by ARSCL AND GOES, May, 2009



All points, May, 2009
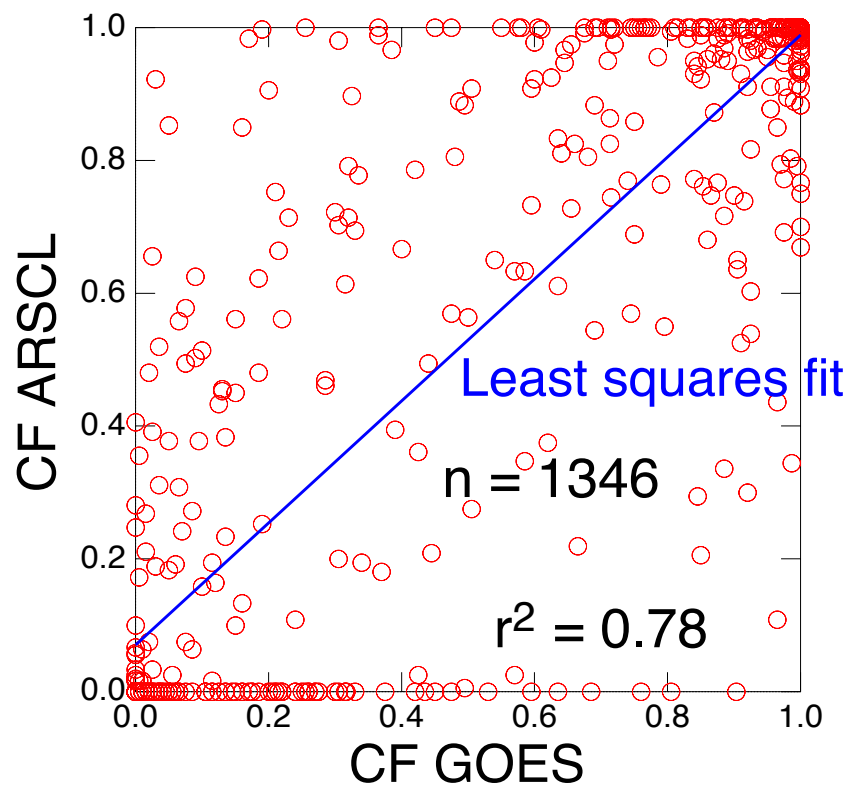
Points within 5% of 0 or 1 in both data sets excluded

Least squares fit

$n = 1346$

$r^2 = 0.78$

$n = 620$

$r^2 = 0.44$
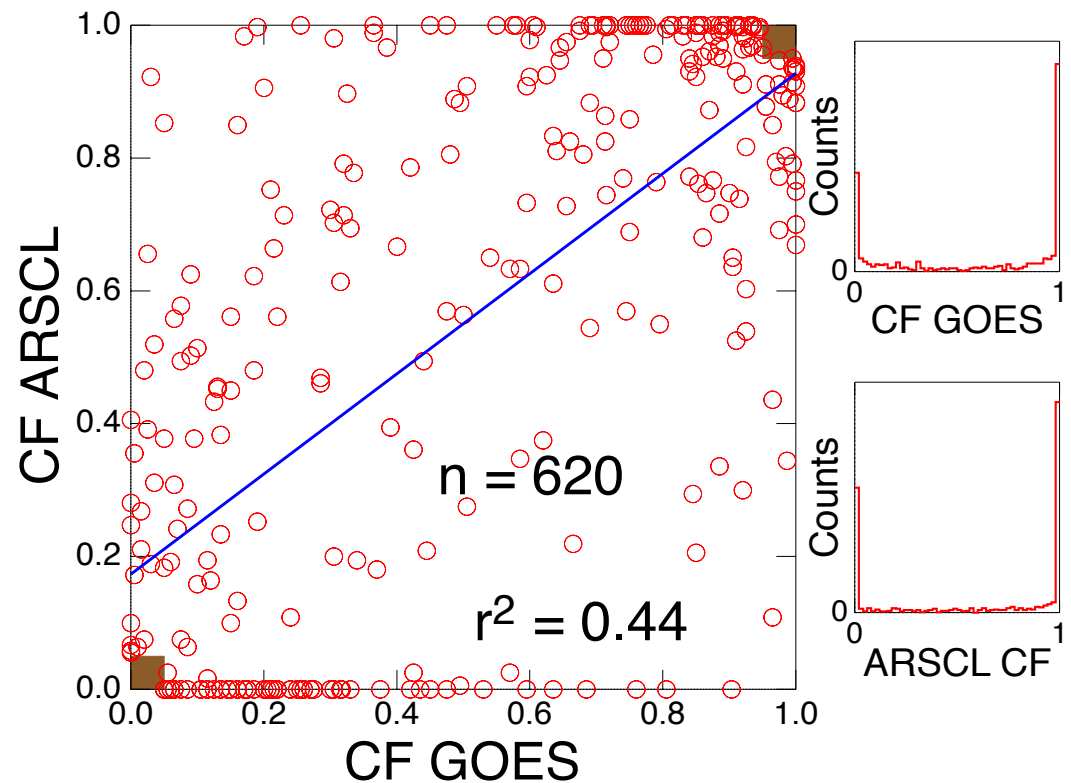
Excluding all-cloud and no-cloud scenes reduces variance accounted for by the regression from 78% to 44%.

# TOTAL SKY IMAGER



Uplooking
convex mirror;
downlooking
camera

Camera
support

Sunblock
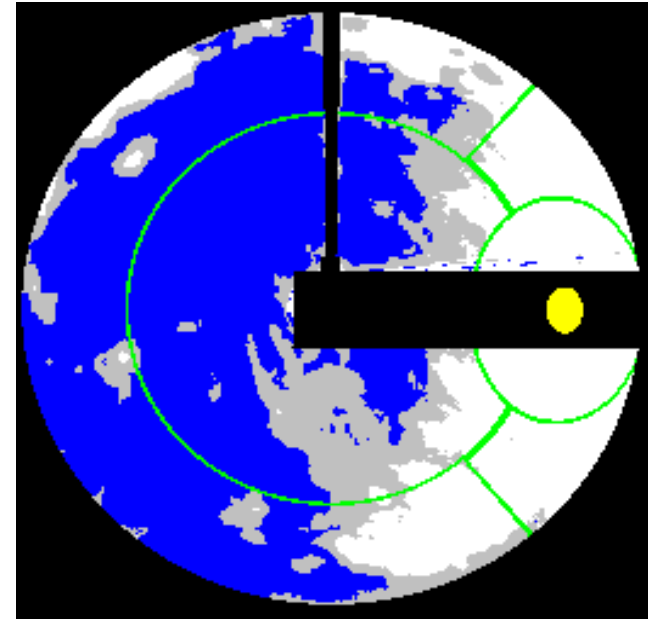
Opaque and
thin cloud masks
as fraction of pixels

Provides thin and thick cloud fraction in 100° and 160° cones about zenith.

Thin and thick cloud based on Red/(Red + Blue) thresholds.

# TIME SERIES OF CLOUD FRACTION BY MULTIPLE METHODS

## ARM SGP site (north central OK) May 13, 2009
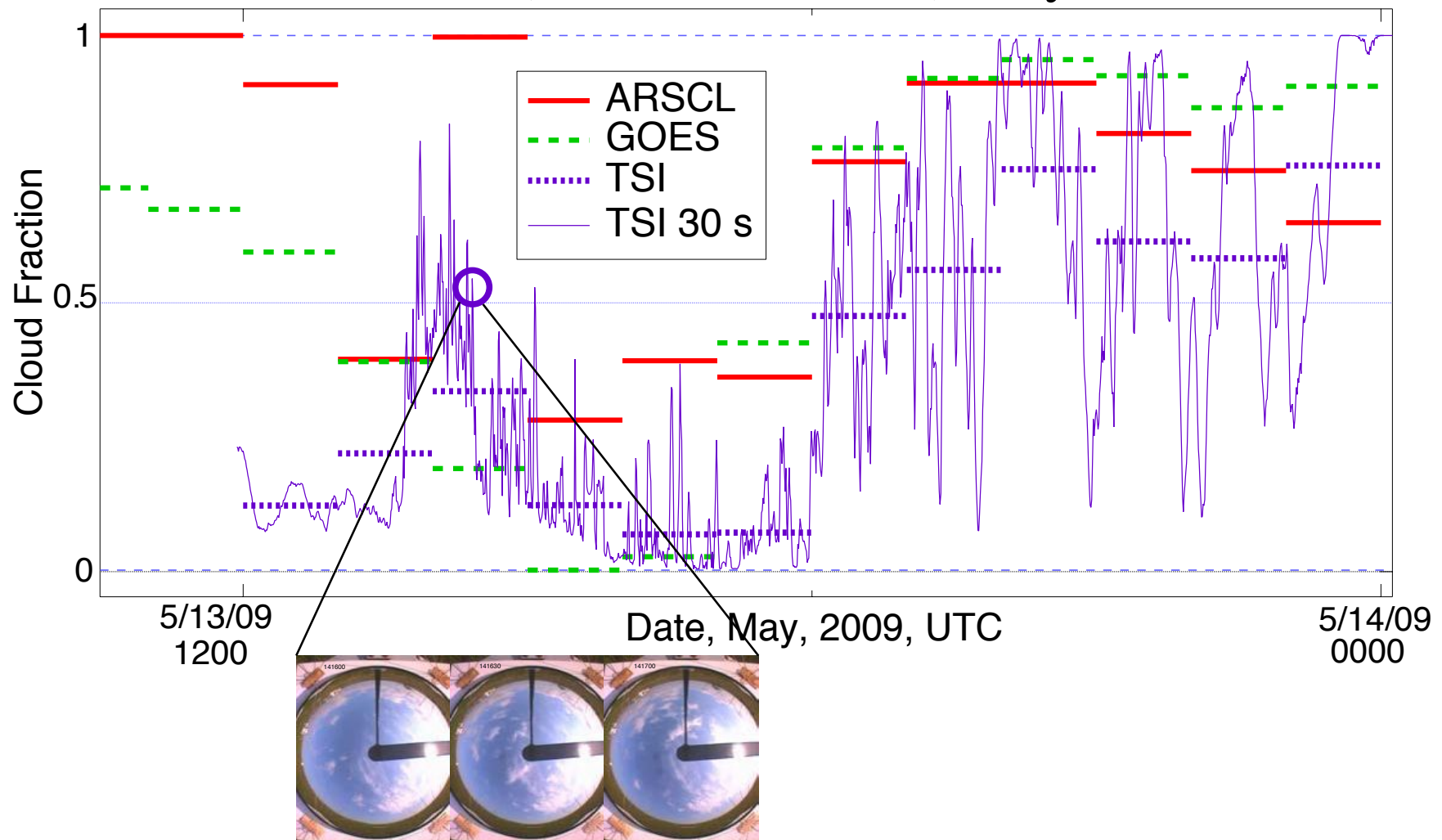


Substantial variation among methods.

Substantial fluctuation in TSI images taken at 30-second intervals.

# TOTAL SKY IMAGES AND CLOUD MASKS FROM TSI ALGORITHM

ARM SGP site (north central OK) May 13, 2009, 1416-1417
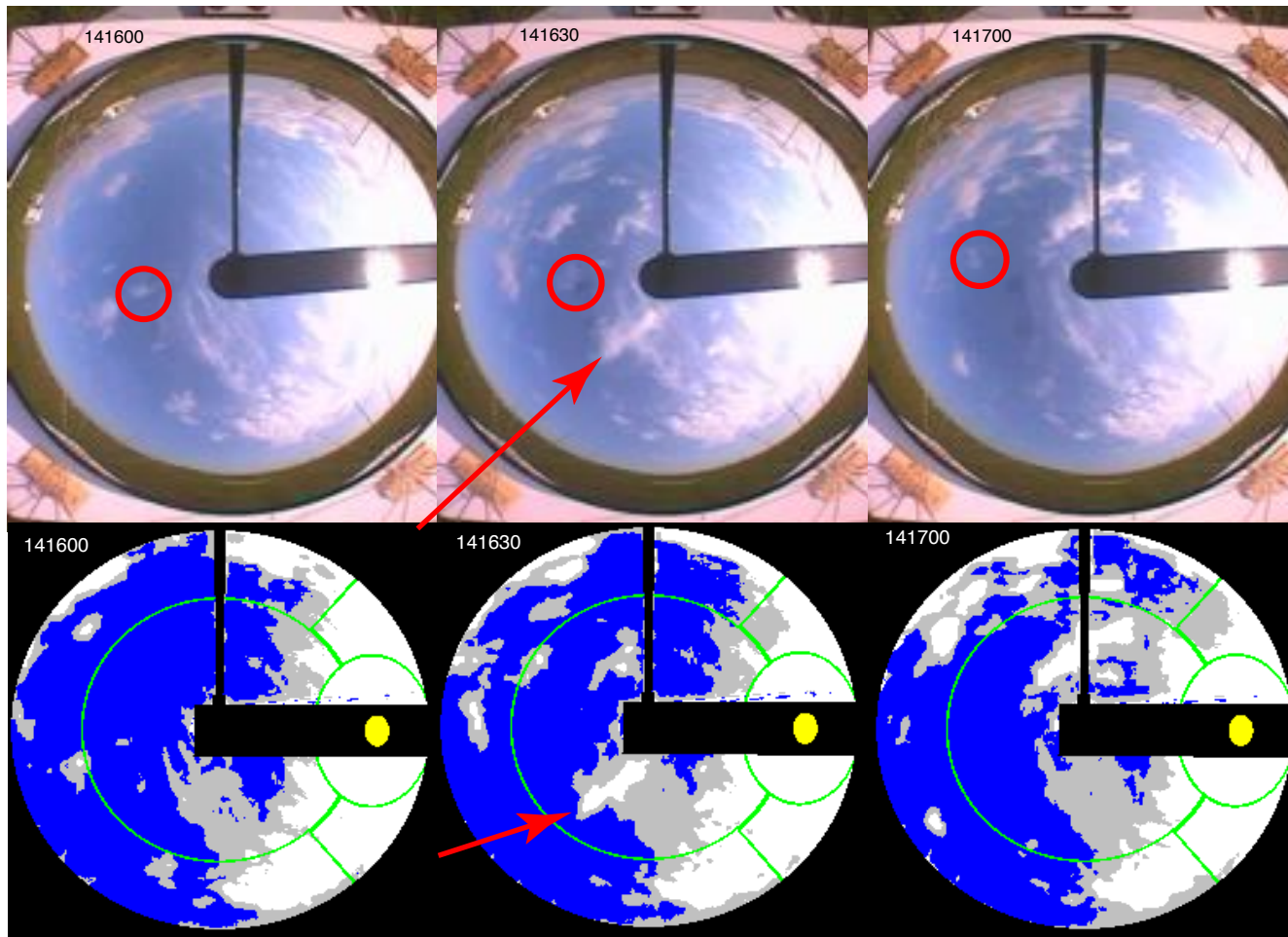


TSI threshold misses thin visible clouds

Substantial changes at 30-s intervals as clouds are blown by wind.

# REASONS FOR DIFFERENCES IN MEASURED CLOUD FRACTION

### Trivial

Mismatch of spatial and/or temporal domain.
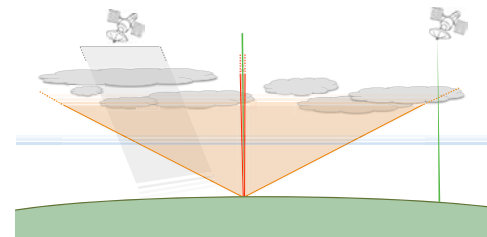
View angle – sidewall effect – cloud aspect ratio.
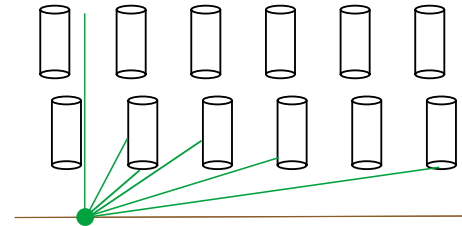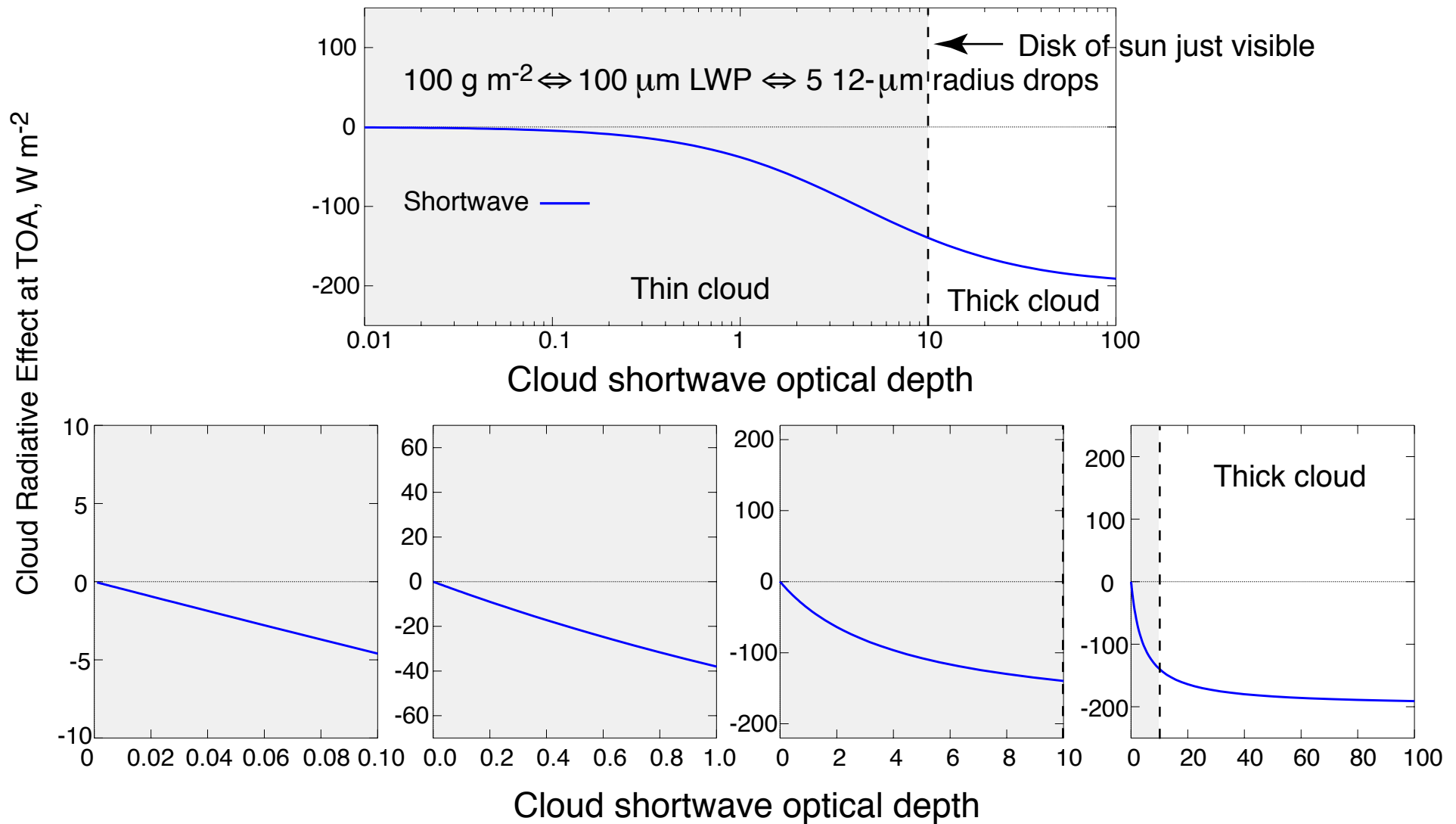
### Intrinsic

Spatial resolution.
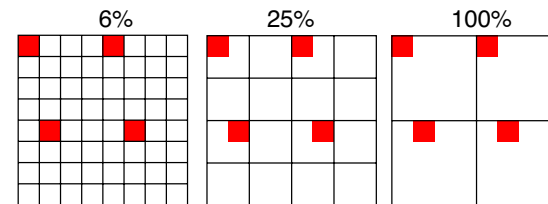
Threshold.
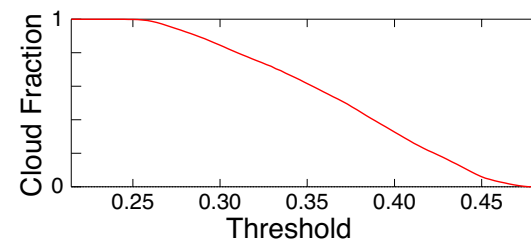
# AND IF WE KNEW CLOUD FRACTION, WOULD IT BE OF ANY USE TO US?

# CLOUD RADIATIVE EFFECT

Dependence on shortwave optical depth and cloud-top temperature
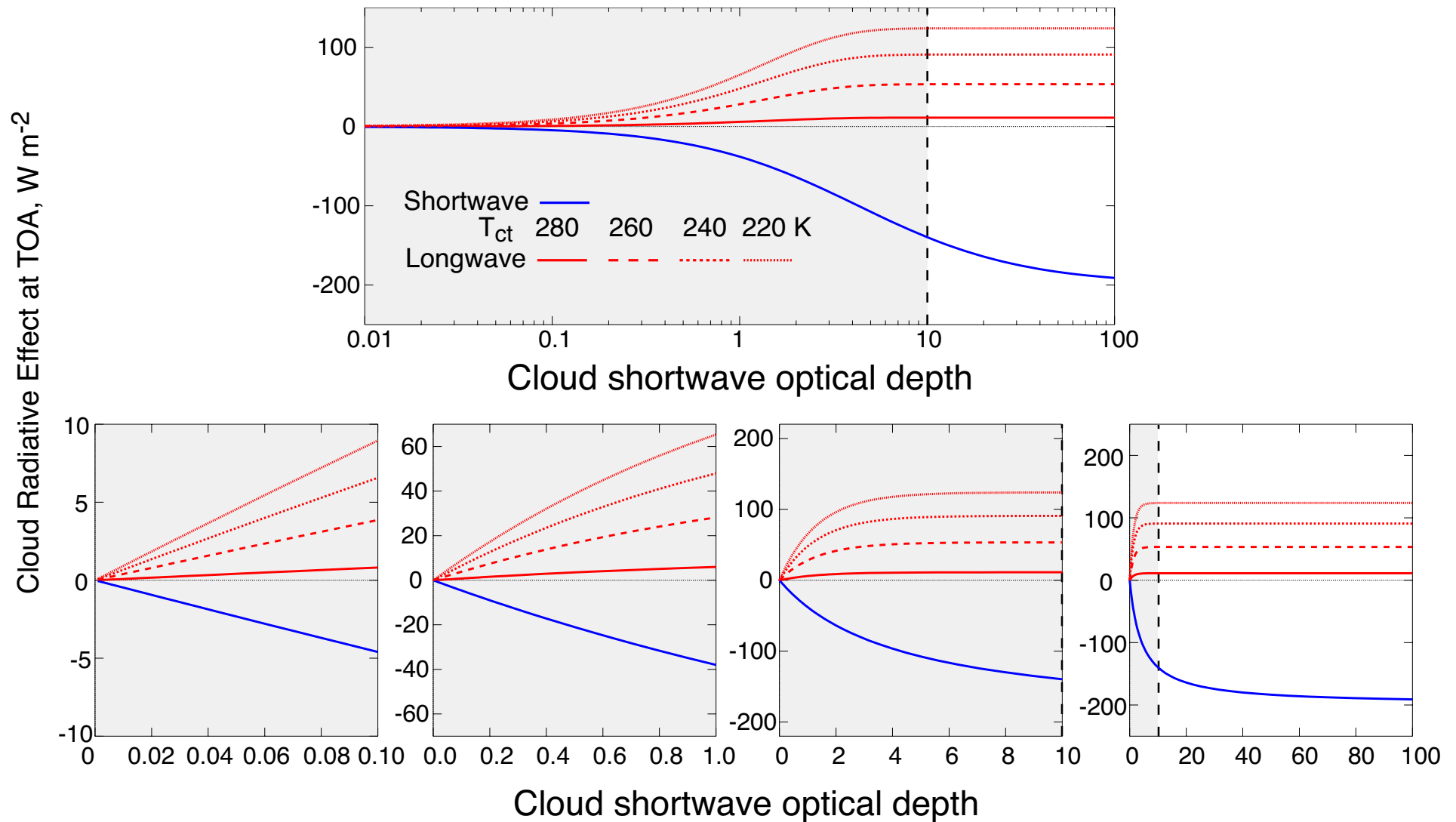24-Hour average CRE, north central Oklahoma, at equinox



CRE is initially linear in optical depth, saturating at high optical depth.

# CLOUD RADIATIVE EFFECT

Dependence on shortwave optical depth and cloud-top temperature
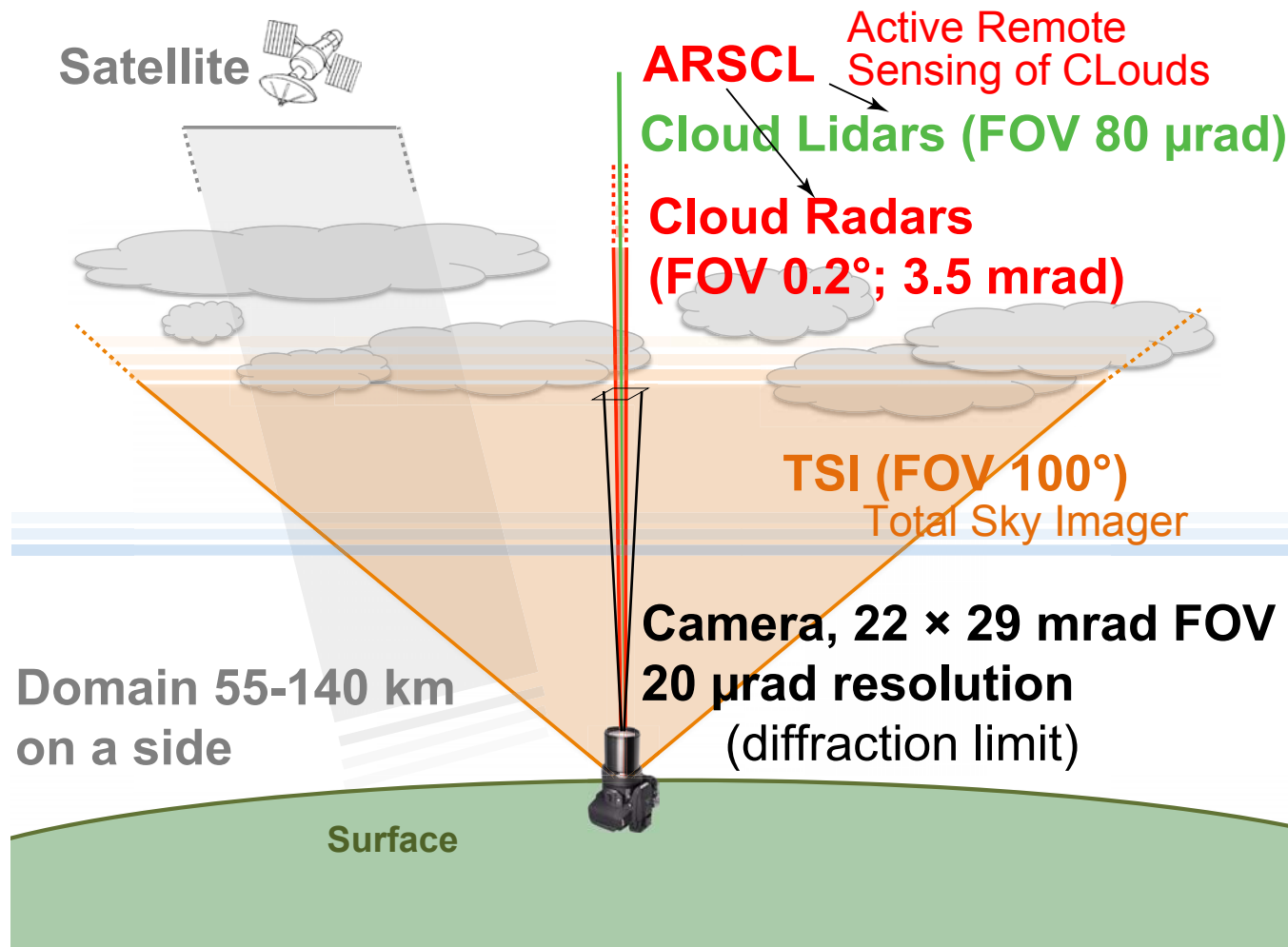
24-Hour average CRE, north central Oklahoma, at equinox



Longwave CRE also initially linear; saturates; depends on cloud-top temp.

# CLOUD RADIATIVE EFFECT

Dependence on shortwave optical depth and cloud-top temperature
24-Hour average CRE, north central Oklahoma, at equinox
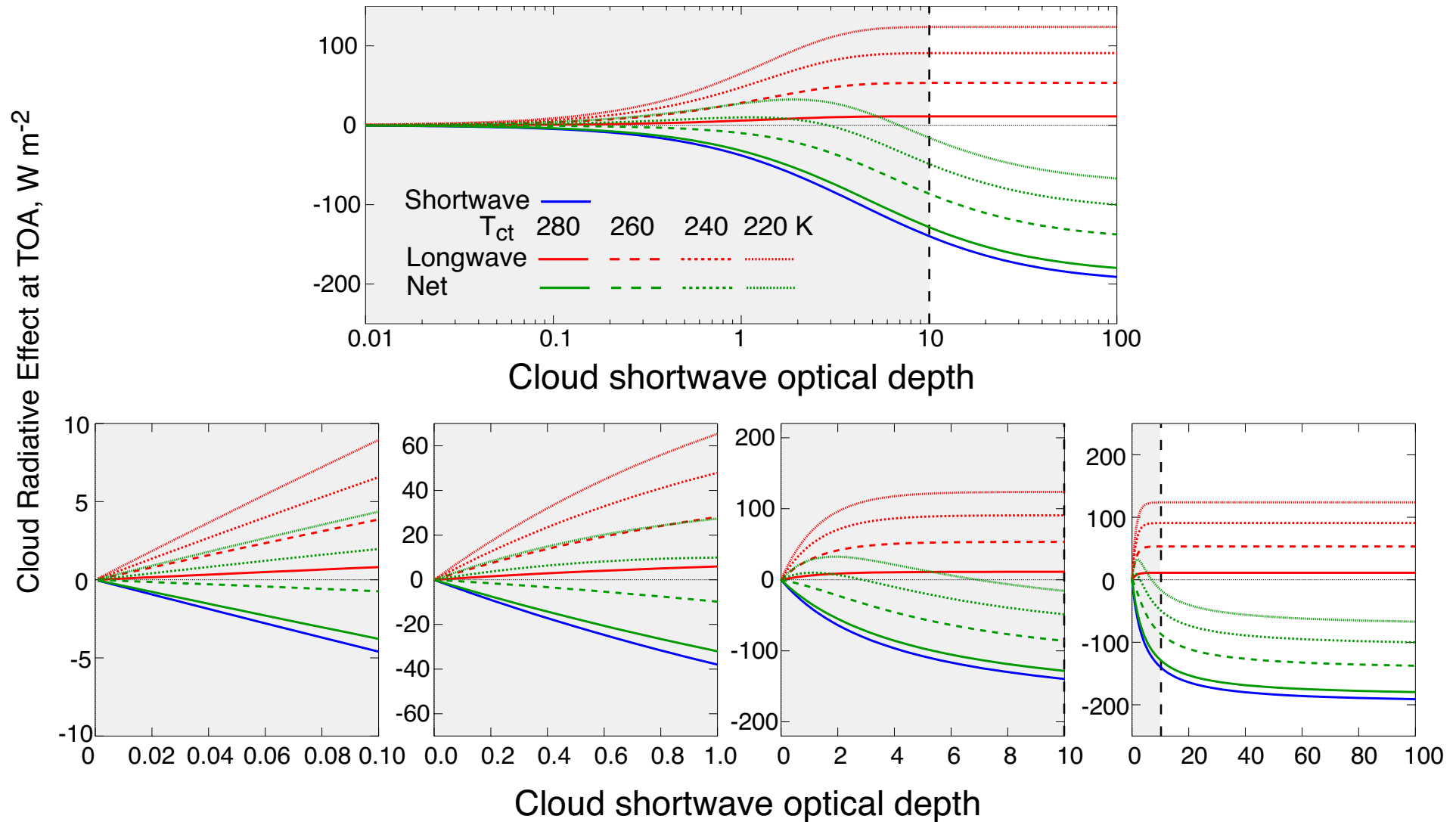
Net CRE depends on optical depth and cloud-top temperature *even in sign*.

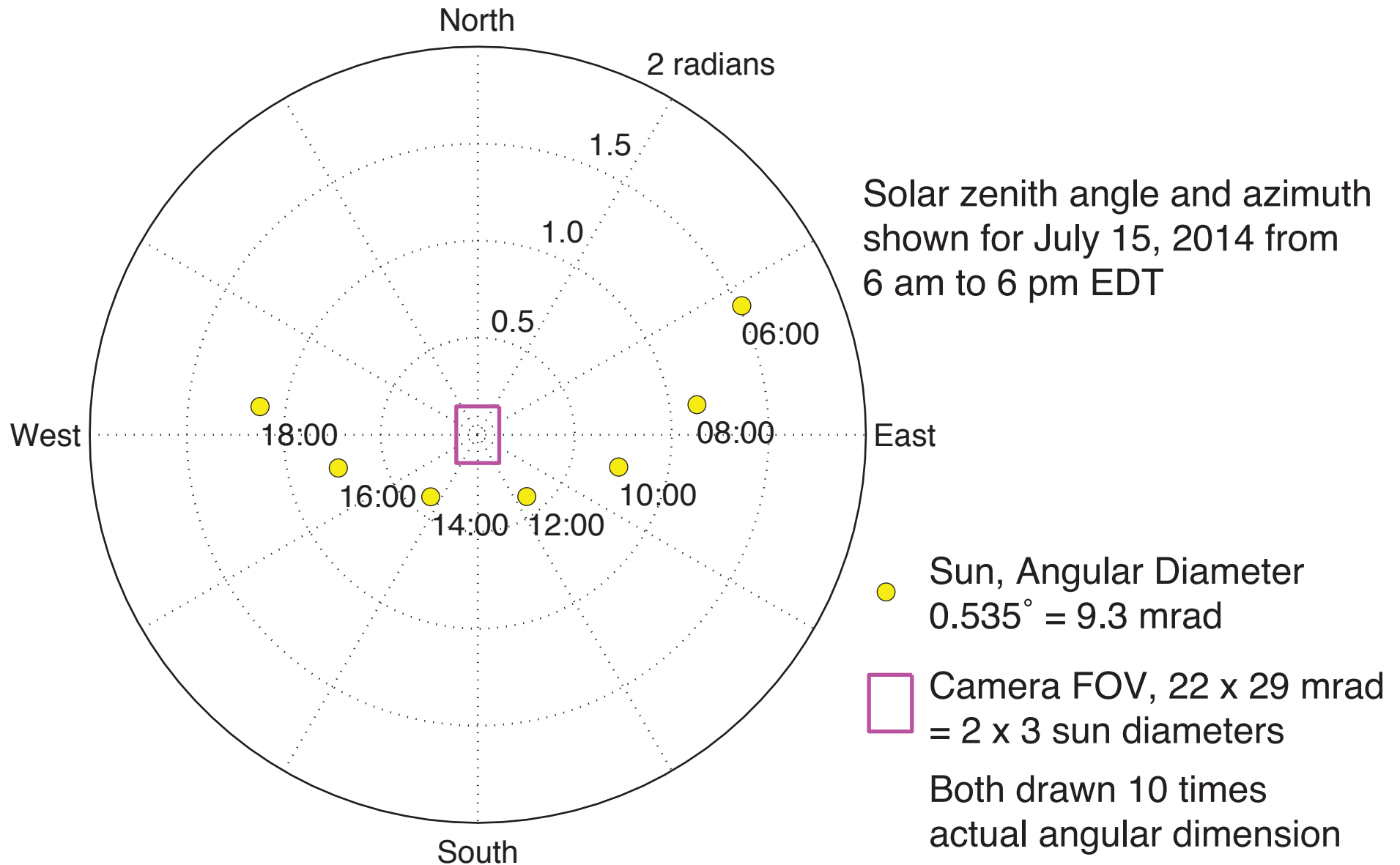WHAT CAN WE LEARN FROM HIGH RESOLUTION SURFACE-BASED IMAGING OF CLOUDS?

# MULTIPLE APPROACHES TO DETERMINING CLOUD FRACTION



**Satellite**

**ARSCL** Active Remote Sensing of CLouds

**Cloud Lidars (FOV 80 μrad)**

**Cloud Radars (FOV 0.2°; 3.5 mrad)**

**TSI (FOV 100°)** Total Sky Imager

**Camera, 22 × 29 mrad FOV 20 μrad resolution** (diffraction limit)

**Domain 55-140 km on a side**

**Surface**

*Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014*

High resolution, narrow field of view camera brings complementary perspective to study of cloud amount and properties.

# OBSERVATION GEOMETRY



North

2 radians

1.5

1.0

0.5

West

East

South

18:00

16:00

14:00 12:00

10:00

08:00

06:00

Solar zenith angle and azimuth shown for July 15, 2014 from 6 am to 6 pm EDT

Sun, Angular Diameter 0.535° = 9.3 mrad

Camera FOV, 22 x 29 mrad = 2 x 3 sun diameters

Both drawn 10 times actual angular dimension

# ZENITH RADIANCE

## How does it depend on cloud optical thickness??
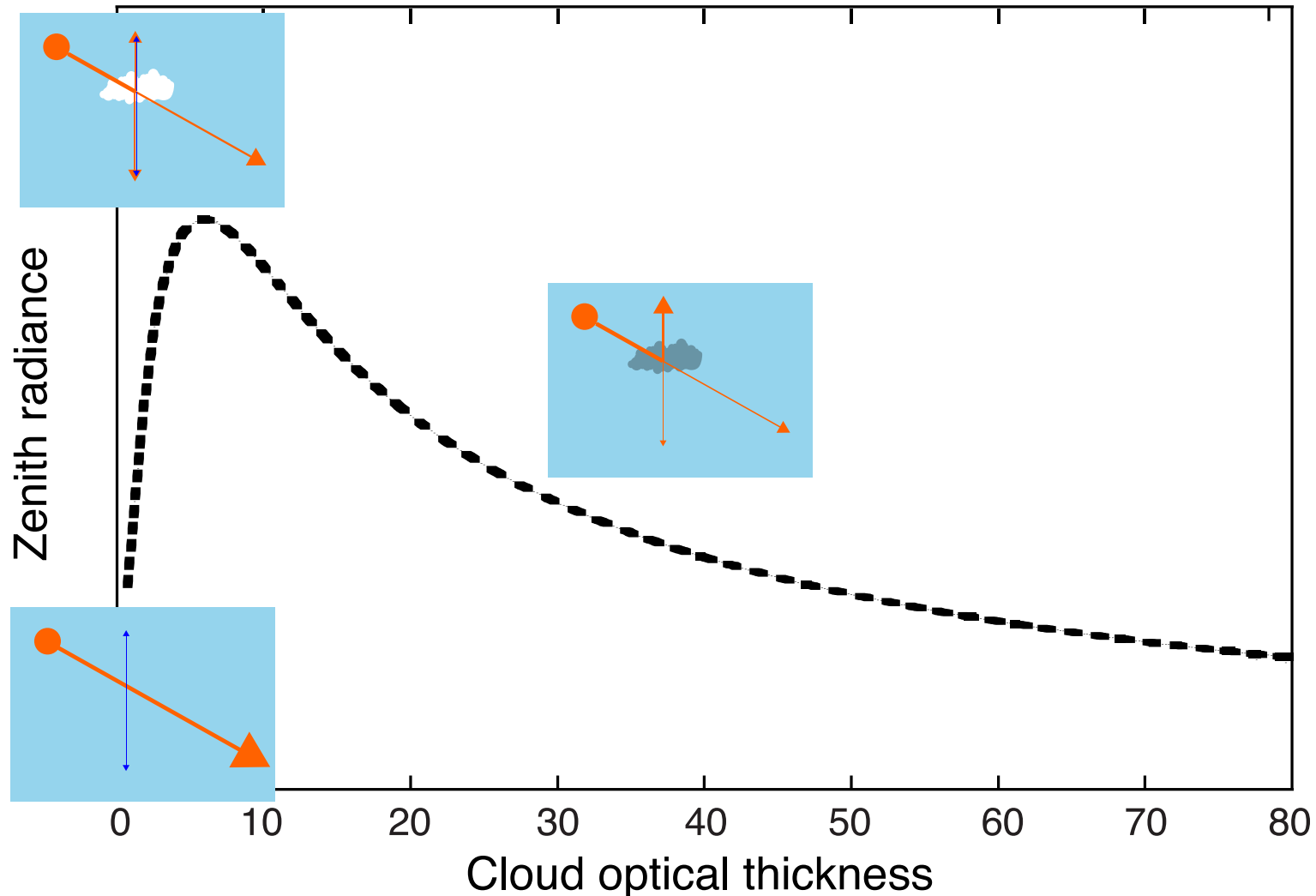


*Modified from Chiu, Marshak, Knyazikhin, Wiscombe, Barker, Barnard and Luo, JGR, 2006*

With increasing cloud optical thickness zenith radiance decreases as reflectance increases and transmittance decreases.

# COMPUTER OPERATING SYSTEM AS CATALOG



S0012627.tif

S0012628.tif

S0012629.tif

S0012630.tif

S0012631.tif

S0012632.tif

S0012633.tif

S0012634.tif

S0012635.tif

S0012636.tif

S0012637.tif

S0012638.tif

S0012639.tif

S0012640.tif

S0012641.tif
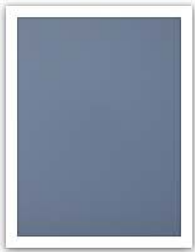
S0012642.tif

S0012643.tif

S0012644.tif

S0012645.tif

S0012646.tif

S0012647.tif

S0012648.tif

S0012649.tif

S0012650.tif

S0012651.tif

S0012652.tif

S0012653.tif

S0012654.tif

# STRENGTHS AND ADVANTAGES

High resolution: 6 μrad nominal (6 mm at 1 km); 20 μrad actual.

Large number of independent measurements: 14 M pixel nominal.

High dynamic range: 16 bit.

Multispectral: three wavelengths nominal: Red, Green, Blue.

Black background of outer space: No surface effects (to first order); Rayleigh radiance is exactly calculable.

No side-wall issues; no correction sky cover to ground cover.

Readily available data acquisition hardware and software.

Available, easy-to-use image-processing software.

Simplicity: Get going right away.

Low cost.

Lots of data!

# WEAKNESSES AND LIMITATIONS

Two-dimensional only.

Daytime only.

Limited wavelength range.

Small fraction of sky.

Extremely local.

Aerosol masquerades as cloud.

Lots of data!

# CAMERA WAVELENGTH RESPONSE

## Comparison with Sun and Sky spectral irradiance
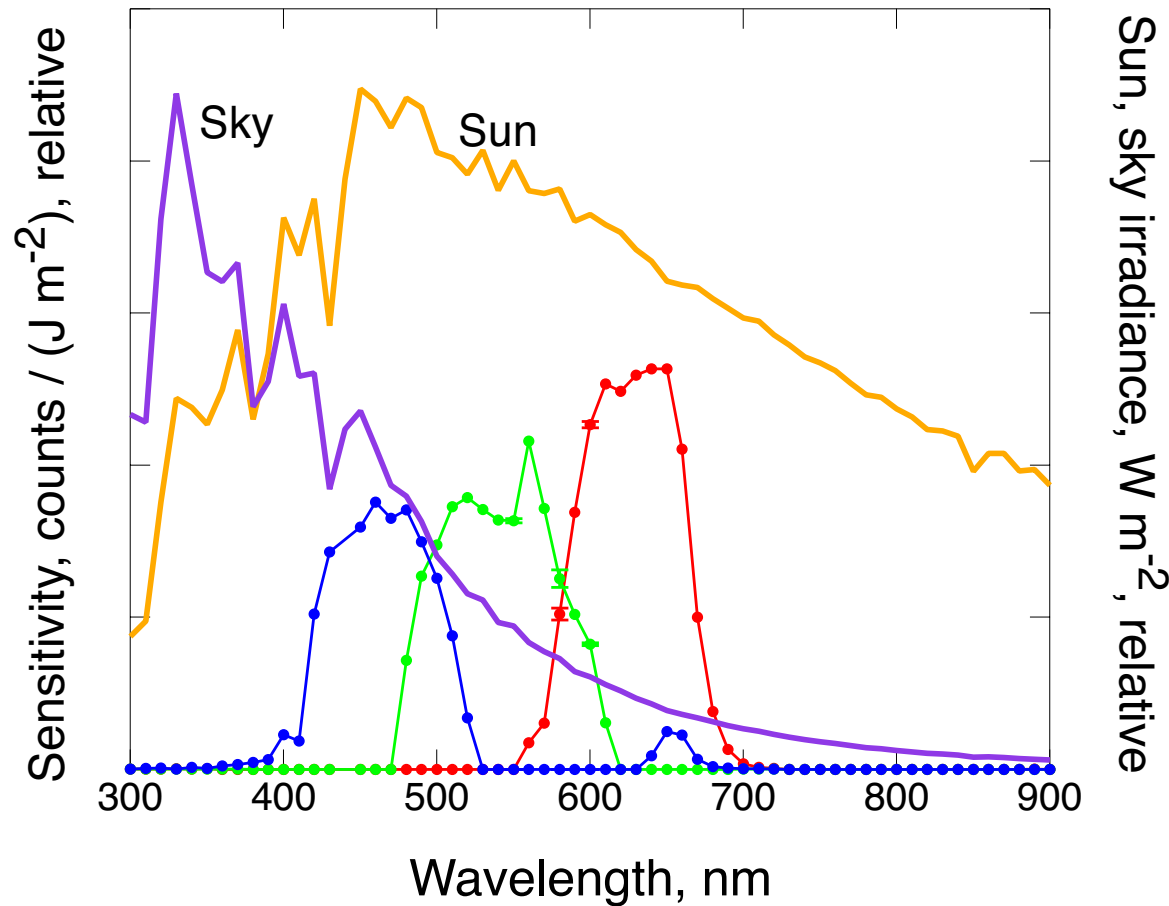


Red and Blue are fairly well separated.

Sun and Sky spectra overlap both Red and Blue, but with different weights.

This can be exploited in distinguishing cloudy and cloud-free sky.
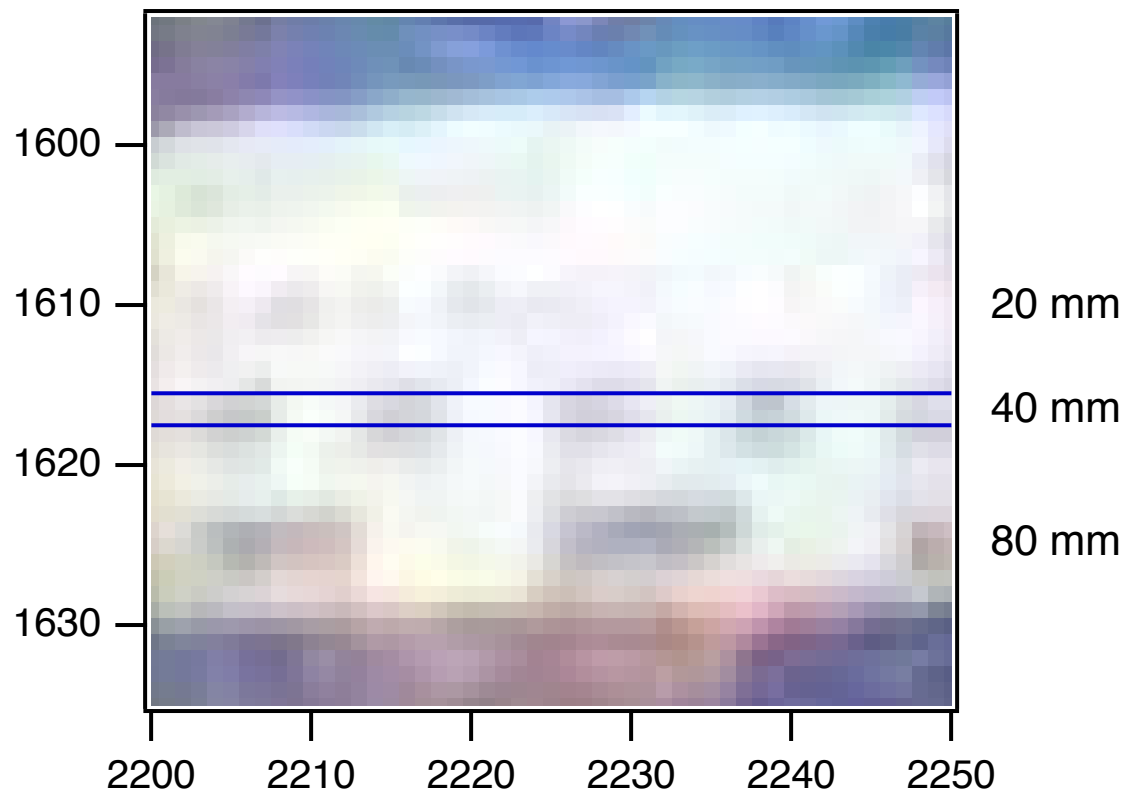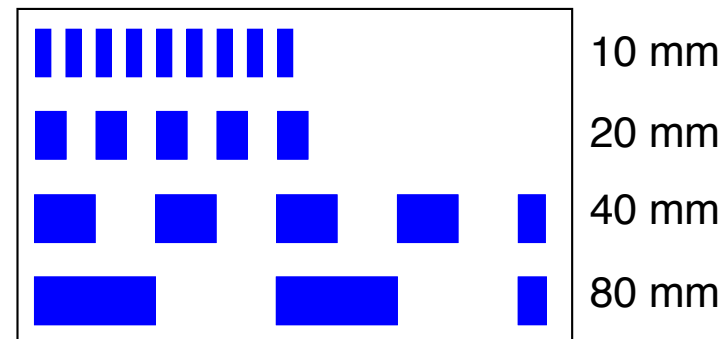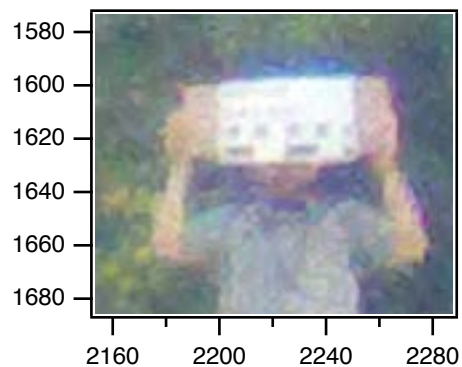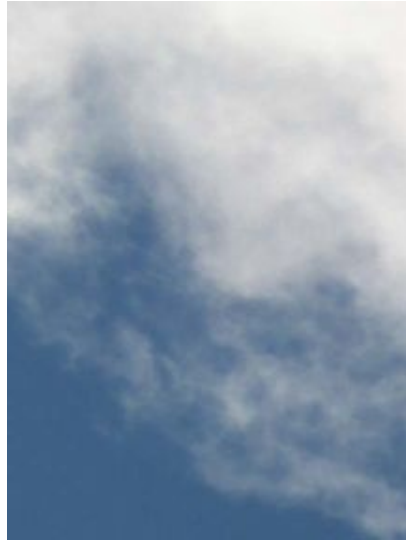
# RESOLVING POWER TEST AT 1 km
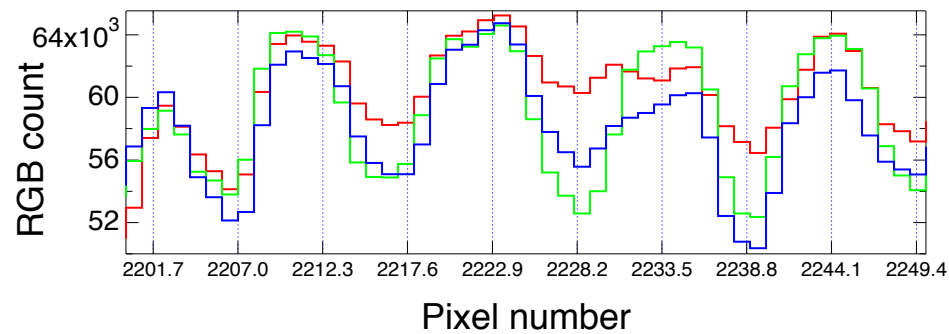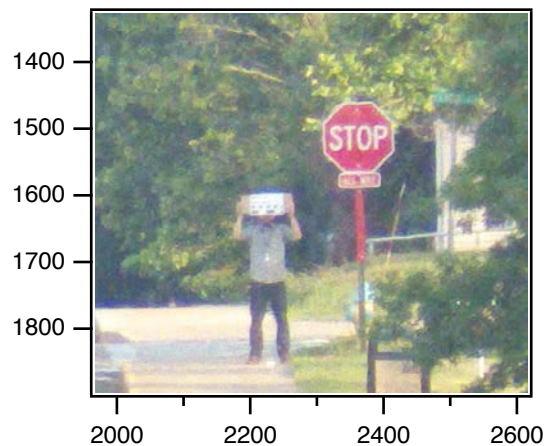
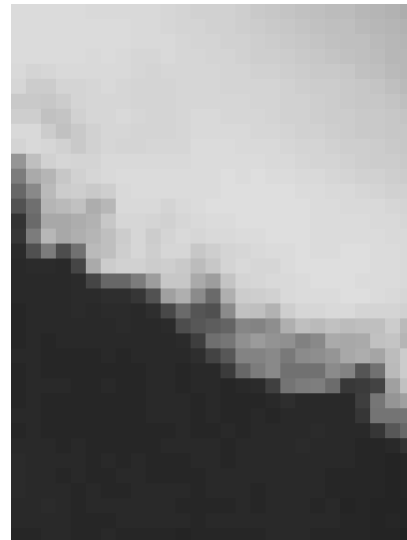# IMAGE PROCESSING AND ANALYSIS TOOLS
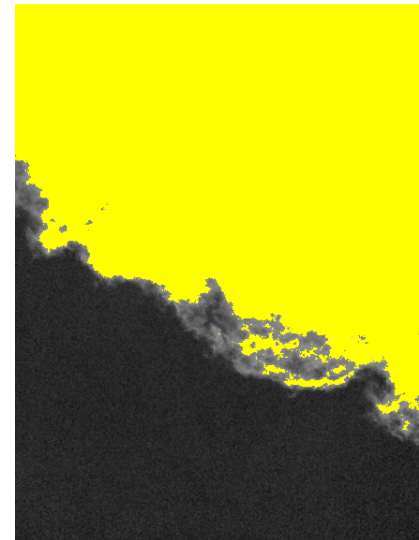
Natural color
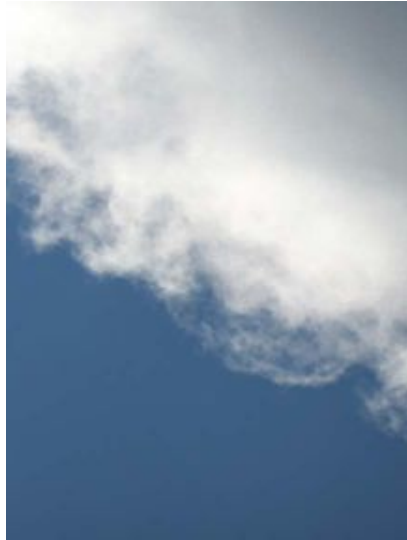
Expand

Expand

Expand

Red

Red/(Red+Blue)

Pixelate

Threshold

# DETERMINING CLOUD FRACTION

## Cloud mask as function of threshold Red/(Red + Blue)



Natural color      Red      Red/(Red + Blue)

Threshold    0.35        0.40        0.45
Cloud Fract 0.618       0.587       0.542
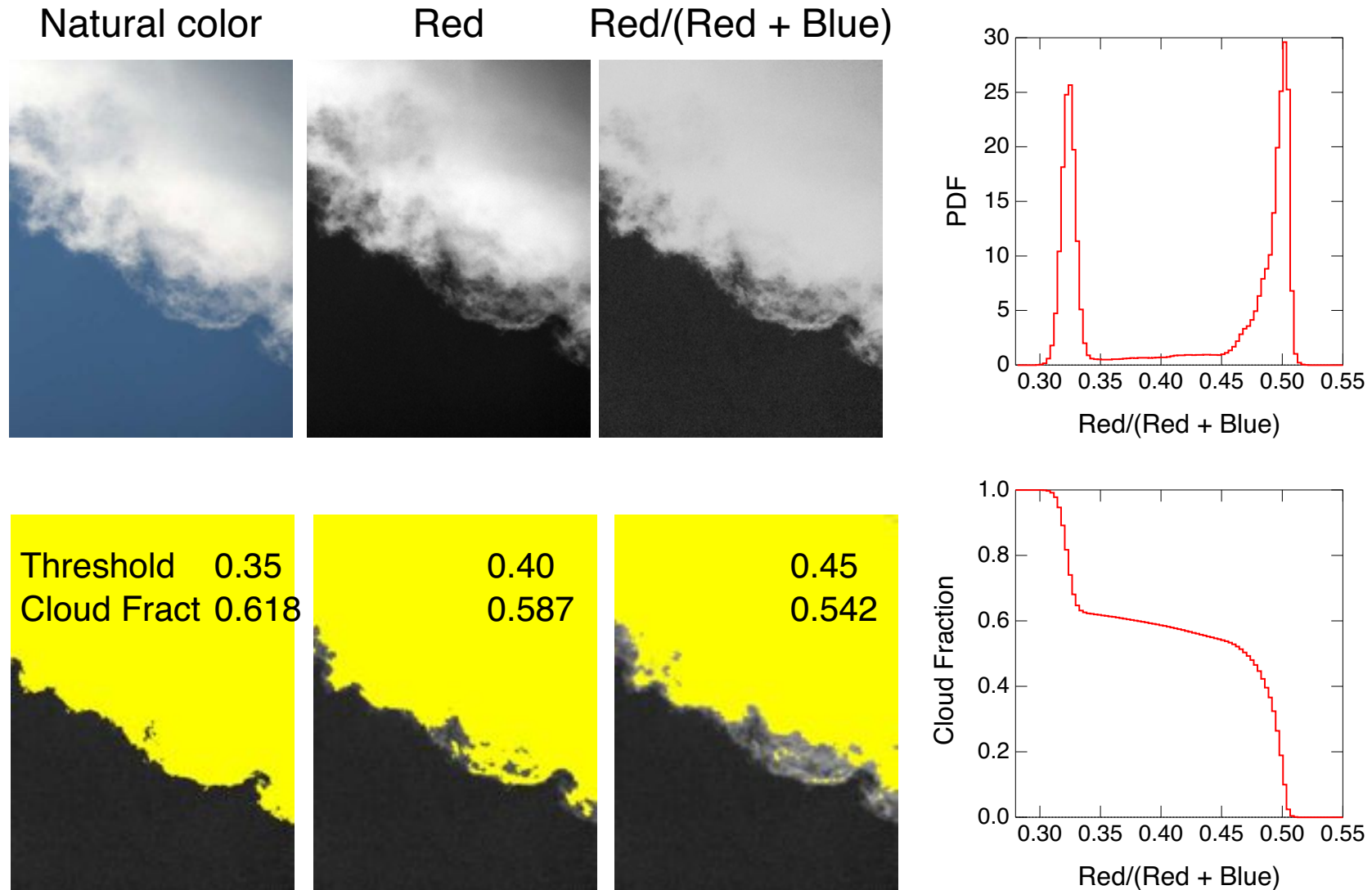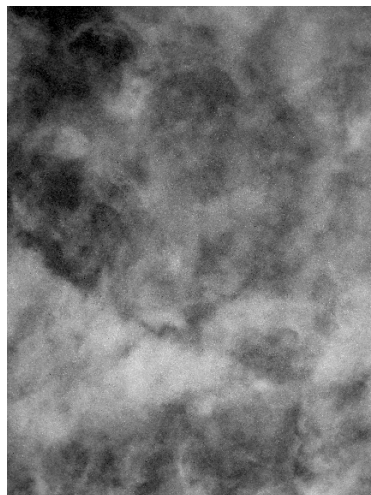
Cloud fraction is constrained between ~0.54 and ~0.62.

# DETERMINING CLOUD FRACTION
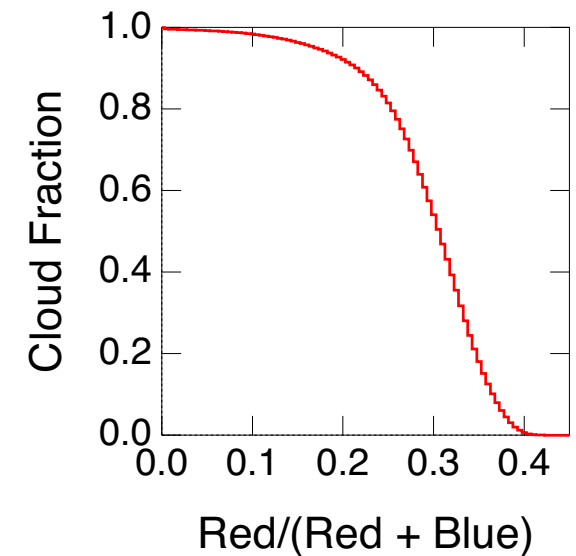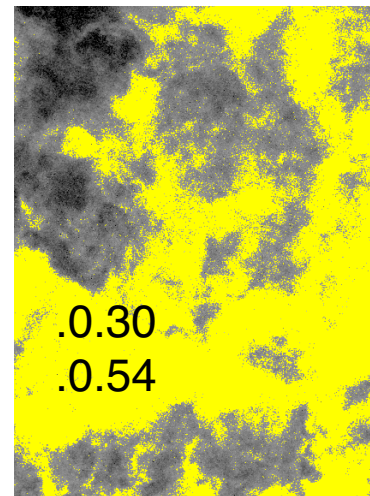
## Cloud mask as function of threshold Red/(Red + Blue)



Natural color · Red · Red/(Red + Blue)

Threshold 0.20 · .0.25 · .0.30
Cloud Fract .0.92 · .0.81 · .0.54
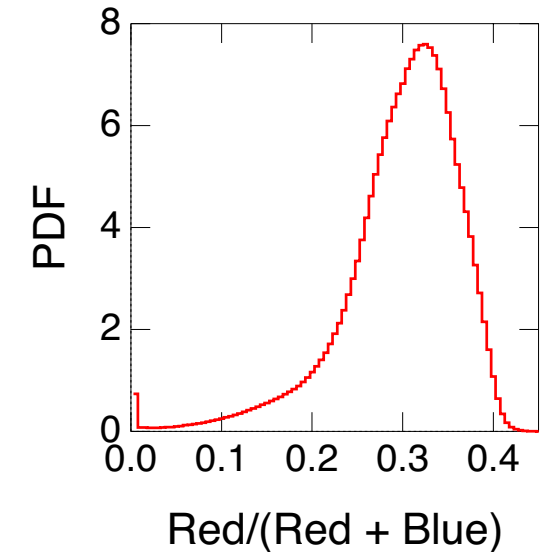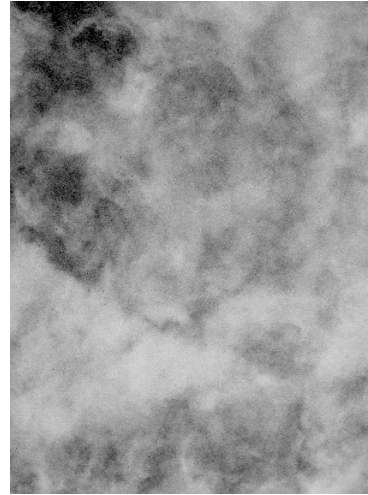
Results in indeterminate cloud fraction.

# DETERMINING CLOUD FRACTION
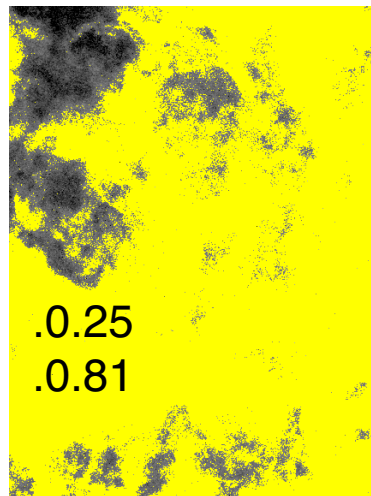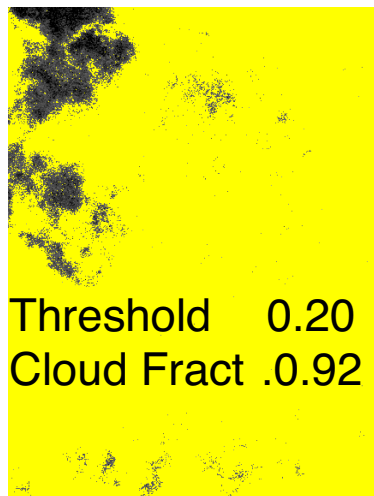
## Cloud mask as function of threshold Red/(Red + Blue)



Natural color     16 x zoom     Red/(Red + Blue)

| Threshold | 0.435 | 0.425 | 0.415 |
|---|---|---|---|
| Cloud Fract | 0.31 | 0.47 | 0.64 |
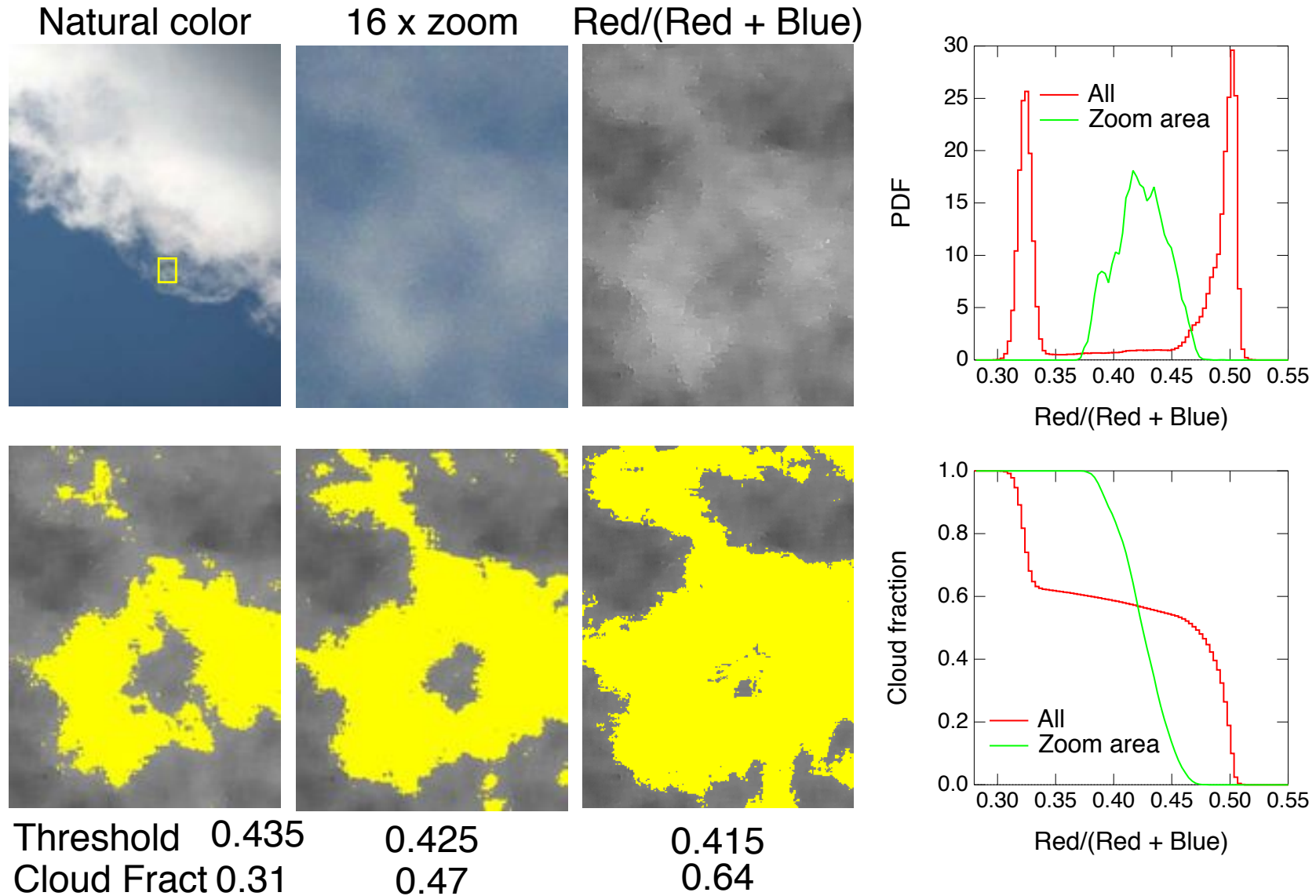
Cloud fraction in zoom area is indeterminate.

# EFFECT OF RESOLUTION ON CLOUD FRACTION

Resolution artificially degraded from 6 μrad to 2 × mrad
at constant threshold

| | Pixels 3456 x 4608 | 27 x 36 | 9 x 12 | 3 x 4 | 1 x 1 |
|---|---|---|---|---|---|



| Row label | | | | | |
|---|---|---|---|---|---|
| Natural color | | | | | |
| R/(R+B) Grayscale | | | | | |
| Cloud fraction | 0.623 | 0.630 | 0.657 | 0.667 | 1.000 |
| Cloud mask at R/(R+B) = 0.34 | | | | | |
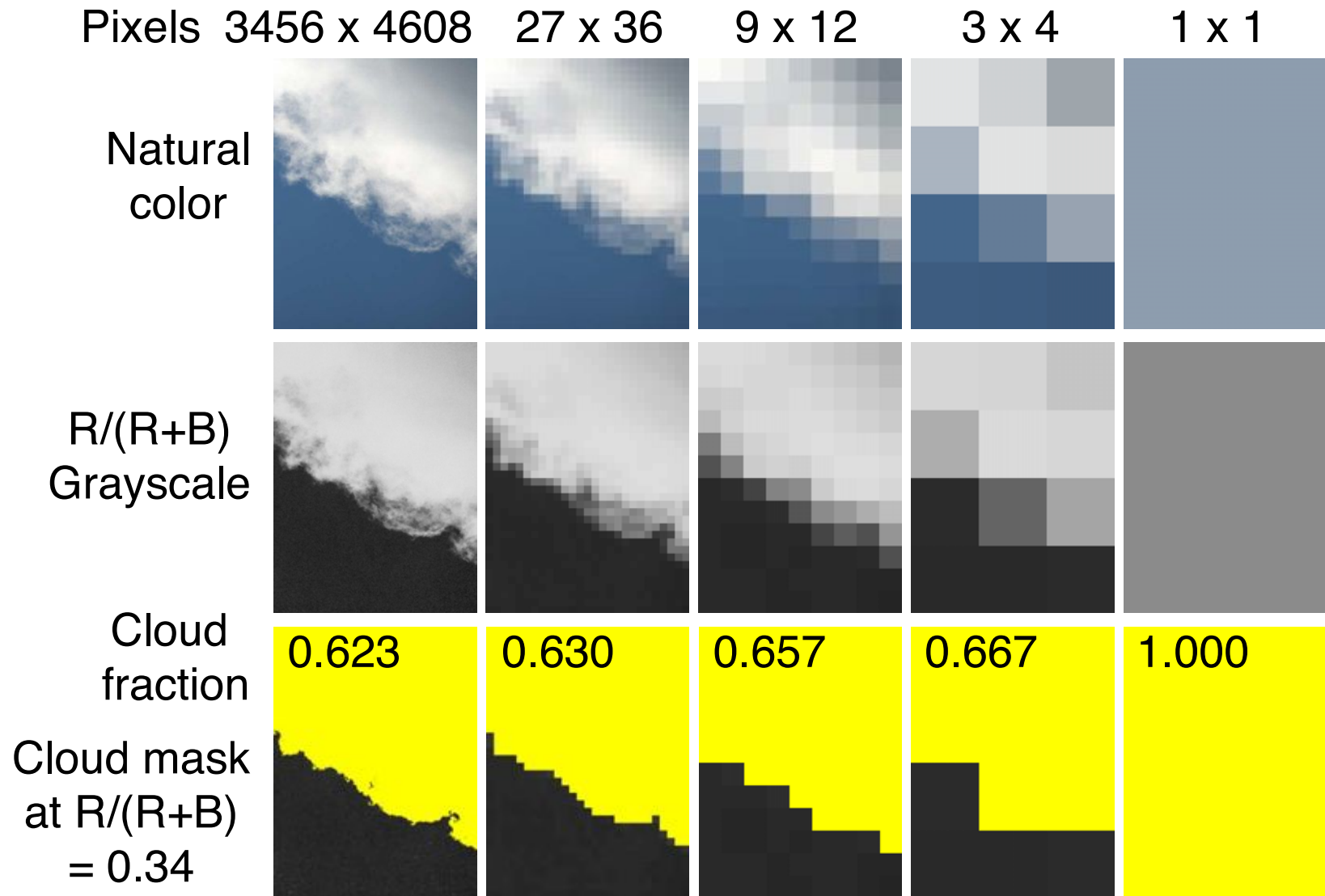
As resolution is degraded, cloud fraction increases.

# EFFECT OF THRESHOLD AND RESOLUTION ON CLOUD FRACTION

## Cloud fraction as resolution is artificially degraded from 6 μrad to 20 × 30 mrad, as function of threshold
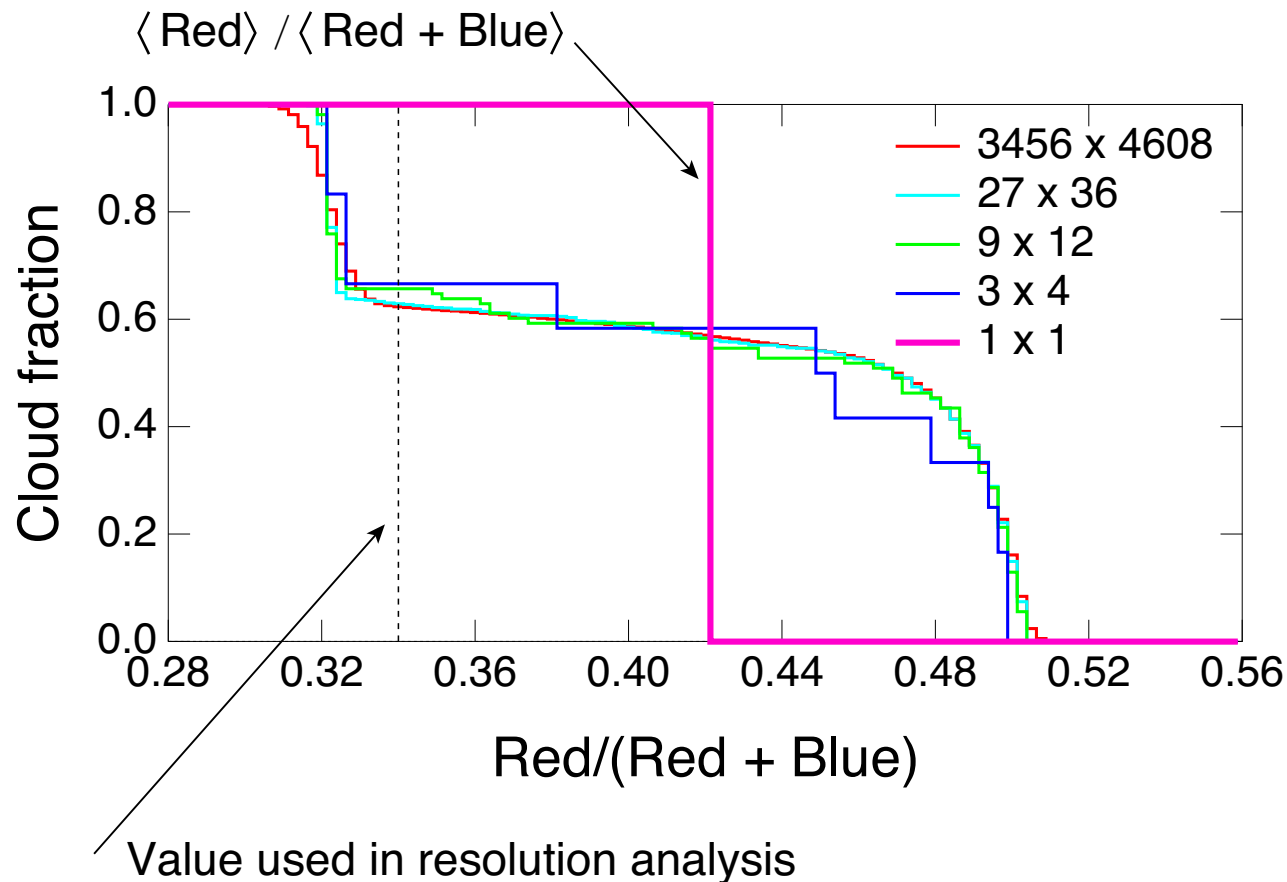


As resolution is degraded, cloud fraction tends to increase if threshold is below mean, and vice versa.
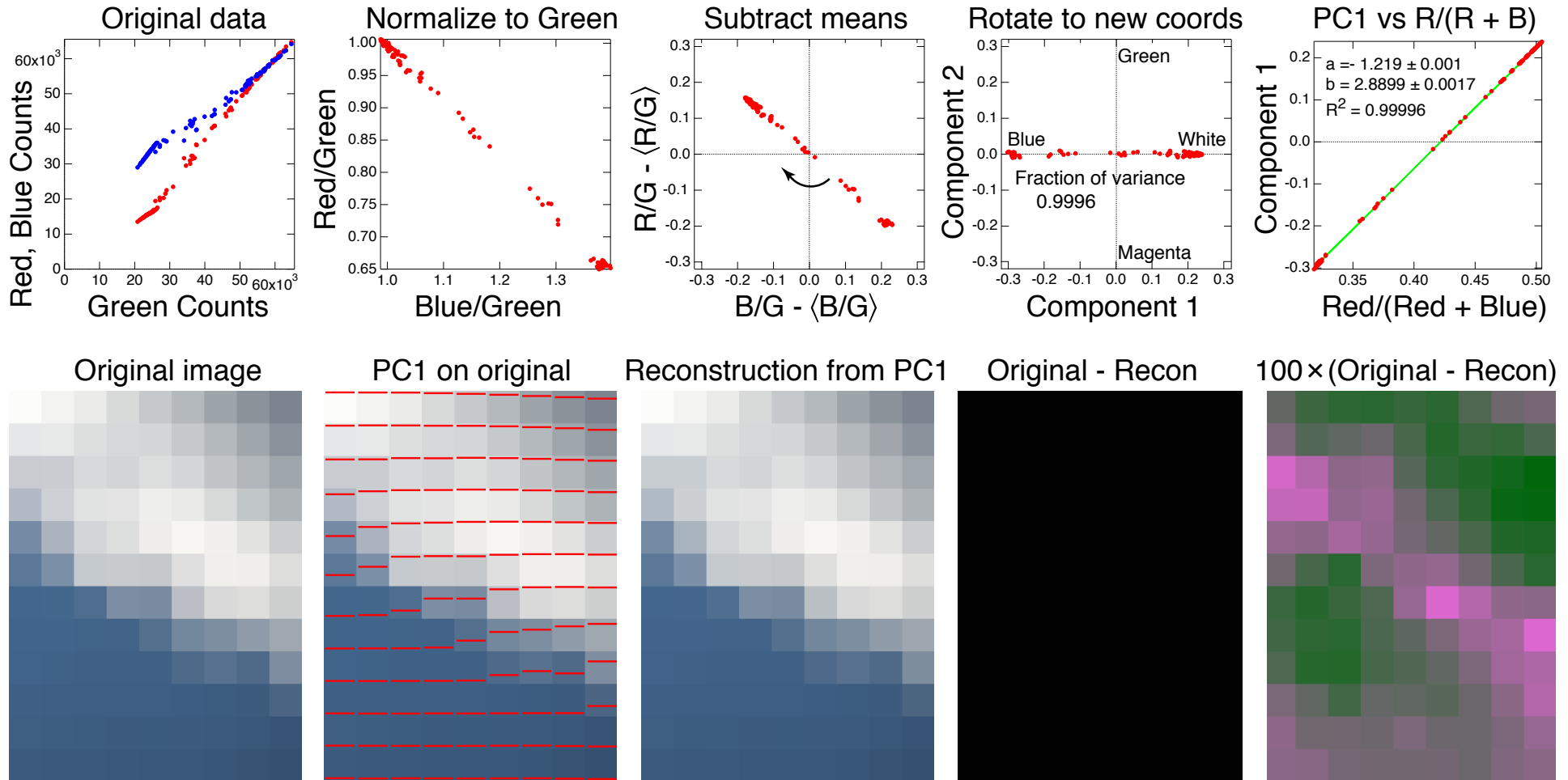
# SUMMARY ON CLOUD FRACTION

CAN IT BE DEFINED? NO!

CAN IT BE MEASURED? NO!

AND IF WE KNEW IT WOULD IT
BE OF ANY USE TO US ANYWAY? NO!

# PRINCIPAL COMPONENT ANALYSIS

## Five easy steps



The color of the original image is accurately reconstructed by a ***single component***.

The first principal component is linearly related to Red/(Red + Blue), which thus serves as a ***quantitative measure of cloud contribution to zenith radiance***.

# A POSSIBLE PATH FORWARD

Use first principal component, PC1, or Red/(Red + Blue), RRB, as ***metric*** of cloud effect on zenith radiance, rather than as a ***discriminant*** of cloud fraction.

$$\frac{\langle \mathsf{Red} \rangle}{\langle \mathsf{Red} \rangle + \langle \mathsf{Blue} \rangle}$$   0.421
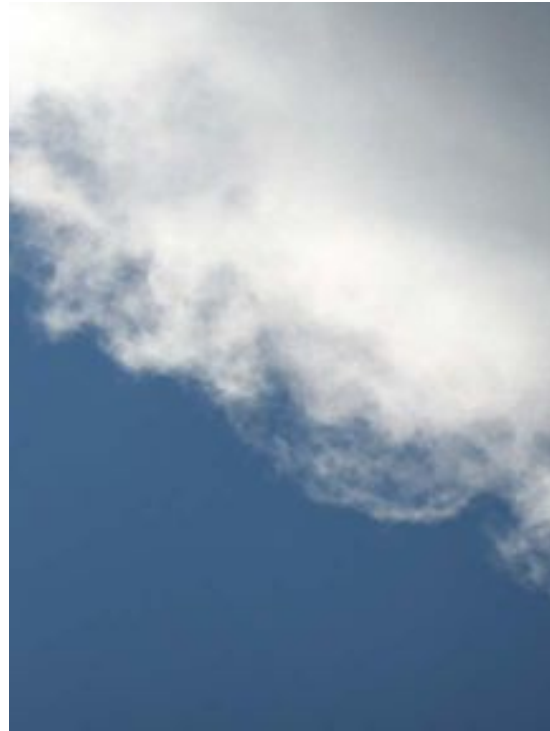
0.295



PC1 and RRB are independent properties of each pixel.

PC1 and RRB are ***continuously variable quantities***, not a binary property (0 or 1) of each pixel.

PC1 and RRB are ***conserved when decreasing resolution***.

# FUTURE DIRECTIONS

Principal component analysis (PCA) allows ***attribution of downwelling radiance*** to blue (sky) and white (cloud) contributions.

As Rayleigh radiance is exactly calculable, determination of PC1 or RRB should allow determination of the decrease in blue (sky) radiance and increase in white (cloud) irradiance due to clouds, on a pixel-by-pixel basis.

Perhaps this can lead to a quantitative determination of Cloud Radiative Effect.

Evaluation of climate models on their ability to represent Cloud Radiative Effect (rather than cloud fraction).